# BRITISH WELDING JOURNAL

1960 FEBRUARY

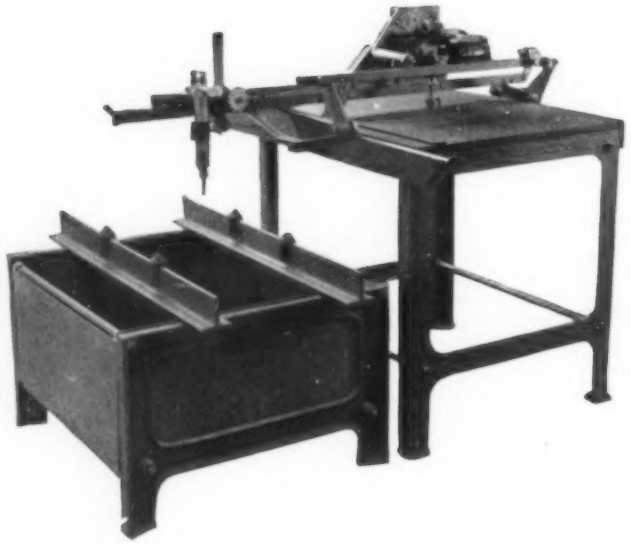
VOL. 7 NO. 2

*CONTENTS*

**ARC PHYSICS CONFERENCE**
The Electric Arc in Welding
*By E. C. Rothasan*
Arc Characteristics
*By D. R. Milner, G. R. Salter, and J. B. Wilkinson*
Gas Absorption
*By G. R. Salter and D. R. Milner*
Metal Transfer
*By J. C. Needham, C. J. Cooksey, and D. R. Milner*
Heat Transfer
*By J. B. Wilkinson and D. R. Milner*

Effect of Arsenic on Weldability of Mild Steel
(BWRA Report)

*maintaining* **B.I.G.** *excellence...*



## the B.I.G. 'Cub' ELECTRICALLY DRIVEN *profile cutting machine*

**Any thickness of steel up to 3"**
**Maximum straight cut 40"**
**Maximum circle 26" dia.**
**Maximum square 26"**
**Maximum rectangular cut 2' 7" x 2' 2"**

**£155-0-0** Ex Works

**Complete with MAGNETIC HEAD for use with steel templates and tracing head for use with wooden templates.**

The "CUB" is the ideal cutting machine for the smaller engineering workshop or maintenance department. Though simple in design it embodies all the qualities essential for clean, accurate and economical profile cutting. The "CUB" is suitable for use with acetylene, propane or coal gases.

Descriptive leaflet available. Demonstration on request.

***If you have a problem B.I.G. technical staff will be pleased to help.***

## British Industrial Gases Limited

**700, GT. CAMBRIDGE RD, ENFIELD, MIDDX.** Telephone: **ENfield 4022, Telex: 22838**

*Sales and Technical Assistance available in most areas*

# International NU-SWIFT News

No. 1

## HAVE YOU MET THESE PEOPLE?

**1.** The new 16-floor skyscraper in BASLE, Switzerland, built and occupied by GEIGY, the world-famous chemical concern, has been equipped with Nu-Swift extinguishers.

**2.** Old-fashioned chemical extinguishers in the SHELL-MEX Building, in the STRAND, LONDON, largest office building in the Commonwealth, have been superseded by reliable Nu-Swift equipment. Built in 1933, the 8,008,462 cubic feet of this giant edifice, which boasts 16 lifts, 6 oil-fired boilers, and 22 miles of water pipes, are now protected by a total of 261 Nu-Swift extinguishers.

**3.** MONTEGO BAY AIRPORT on the North Coast of Jamaica, well-known to sun-hungry socialites in U.S.A. and Britain, is now safeguarded by Nu-Swift. So is the exclusive TOWER ISLE HOTEL.

**4.** In gay VIENNA, 30 break-down vehicles belonging to the TOURING CLUB OF AUSTRIA (similar to the British A.A. service) have recently been equipped with Nu-Swift. Another 31 vehicles in GRAZ have been similarly protected.

**5.** In STOCKHOLM, beautiful capital of Sweden, a rush order for 1½ tons of extinguishers was recently executed by Nu-Swift sales concessionaires in 6 hours. The number of extinguishers required was 60. SKF, ASEA and STORA KOPPARBERGS BERGSLAGS A/B (the oldest industrial undertaking in the world), are among other industrial giants in fast-moving Sweden, who have standardised on reliable Nu-Swift Dry Powder Extinguishers.

**6.** If overtaken by the LAKE POLICE while speeding on the 20-mile long LAKE ZURICH, you will find their patrol boats equipped with Elland-made Nu-Swift Dry Powder Extinguishers, Model 1604. Ashore, this also applies to the police cars and garages of the City and Kanton of busy and prosperous ZURICH.

## HAVE YOU BEEN TO THESE PLACES?

**7.** Direct rail connections link COPENHAGEN with Rome, Paris, Vienna, Venice, etc. THE DANISH STATE RAILWAYS have now equipped all international coaches starting from the up-to-date capital of Denmark, with Nu-Swift.

**8.** MR. HUGH DALTON, M.P., Chancellor of the Exchequer in the post-war Labour Government (1945–50), is the latest prominent politician to equip his home with Nu-Swift.

**9.** After exhaustive tests, extending over several years, the AUSTRALIAN ARMY have satisfied themselves that Nu-Swift Dry Powder Extinguisher Model 1604, meets their exacting requirements. The first orders have been placed.

**10.** More than 50% of all new NORWEGIAN vessels, mainly TANKERS, are protected by Nu-Swift.

**11.** Prince FAROUK, now a citizen of Monaco, but once King of EGYPT, one day when shooting in the desert near Cairo, saw his car ablaze. Fire was put out by a local Nu-Swift enthusiast. Result: The King had all his palaces and his yacht protected by Nu-Swift.

**12.** The underground aeroplane factories of SAAB (SVENSKA AEROPLANE A/B) Linköping, Sweden, are protected by Nu-Swift. So are the naval vessels in the ATOM-BOMB-PROOF UNDERGROUND HARBOUR near Stockholm, built into the mountain by the cautious Swedes.

**13.** In far-off FIJI, where cannibalism was rife within living memory, the recently constructed BROADCASTING STATION is protected against fire by Nu-Swift. So is the new AUTOMATIC TELEPHONE EXCHANGE.

**14.** An animated correspondence with G. BERNARD SHAW resulted in 1944 from an enquiry by the ever-alert but critical sage. Asked by Shaw why, in our letter of reply, no prices were quoted, a cheeky Nu-Swift clerk retorted that "We thought you wanted to protect your life, not your purse. Does price matter when your life is at stake?" G.B.S. rose to the bait by replying: "Please treat me as a prospective customer, not as a back-chat comedian."

**15.** SWISS FEDERAL RAILWAYS one of the most efficient and modern railway systems in the world, have placed their first orders for Nu-Swift extinguishers.

**16.** Mr. W. J. SCOTT, Q.C., FIRE MARSHAL OF THE PROVINCE OF ONTARIO, during a recent lightning trip to Europe, as Dominion Government NATO delegate, included Elland in his itinerary. On his return, having also called at London, Paris, Rome and Madrid, he stated that the visit to Nu-Swift Factory remained the highlight of his European tour, and caused orders to be placed for sample and demonstration extinguishers for the new Ontario Fire Service College at GRAVENHURST, 80 miles from TORONTO.

**17.** Since THE SUDAN gained her independence, the authorities have decided to standardize on Nu-Swift. The first orders have arrived from Khartoum.

**18.** In KUWAIT, fabulously wealthy Arabian oil-well state on the Persian Gulf, police and army cars are now all protected by Nu-Swift.

**19.** The SOUTH AFRICAN ELECTRICITY SUPPLY COMMISSION have decided to place Nu-Swift Dry Powder Extinguisher, Model 1604, on all their breakdown and service vehicles. The first orders have been placed.

**20.** In NIGERIA, Africa, which is shortly expected to achieve independence, TRAINS AND HOSPITALS are equipped with Nu-Swift. Climate is hot and humid.

**DISASTROUS FIRES CRIPPLE INDUSTRY,**

**—be ready with the best equipment available: NU-SWIFT.**

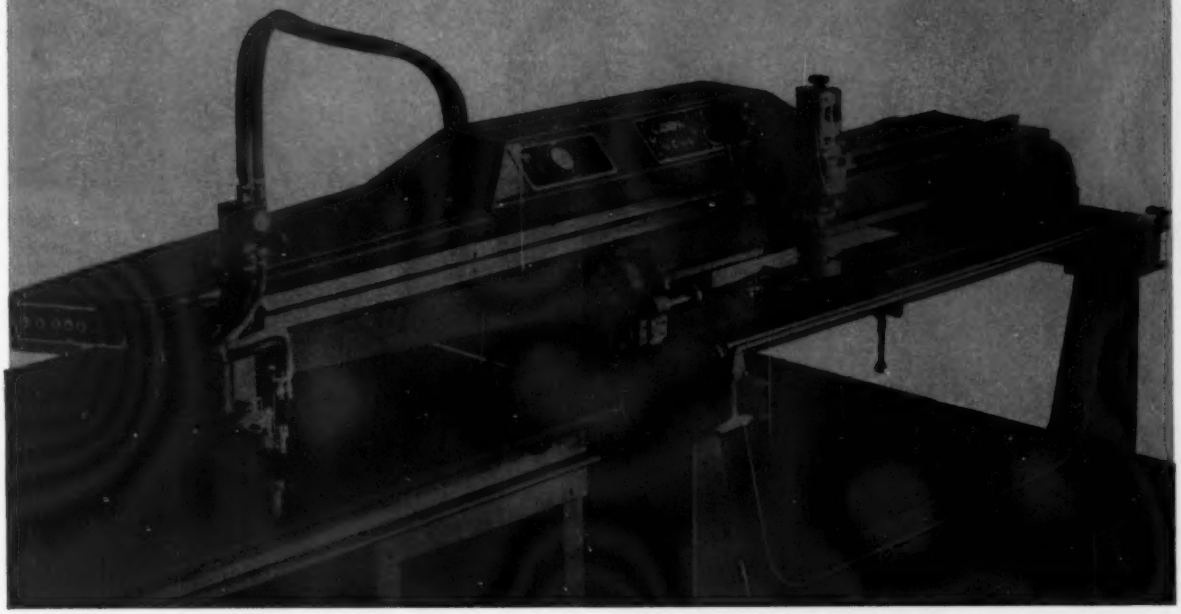
**NU-SWIFT LTD · ELLAND · YORKSHIRE · ENGLAND**

ORDER
FROM THE
G.E.C.

THE GENERAL ELECTRIC CO. LTD., MAGNET HOUSE, KINGSWAY, LONDON, W.C.2

# new

# HANCOMATIC OXYGEN CUTTING MACHINE



## Now available in 90" & 120" cutting widths

**Hancomatics!** Today's finest range of dual carriage oxygen profiling machines. In addition to machines with 40" and 62" cutting widths, there are now Hancomatics with 90" and 120" cutting widths. Hancomatic means top speed, precision cutting — every time; as clean as nearly 40 years specialist experience in cutting can ensure.

**NEW sleek enclosed machine tool appearance, protecting moving parts from dirt and dust.**

**NEW rigid box construction.**

**NEW electrically operated cutting oxygen valve with instant shut-off.**

**NEW tracer head for operation from all types of template.**

★ The 120" width machine is *Britain's largest*. A standard machine of this type can be equipped for a cutting area of as much as 500 square ft.

The new Hancomatic embodies the best principles of oxygen cutting in a handsome, enclosed streamlined machine. Take a big step towards streamlining your production. *Write for details:*

***. . . and the NEW***
**Electronic HANCOLINE**
**traces from pencil drawing *automatically***

★ Cut width compensation — on tracer head.

★ No need for templates.

★ Equipped with the Hancock patented roller drive — no physical contact between tracer and drawing.

★ Supremely simple in operation.

**Available with 38", 60", 90" and 120" cutting widths.**

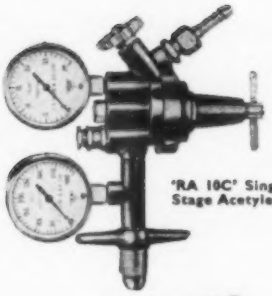
*Send for descriptive leaflet.*

**HANCOCK & CO. (Engineers) LTD.**
PROGRESS WAY · CROYDON · SURREY · *Telephone:* CROydon 1908

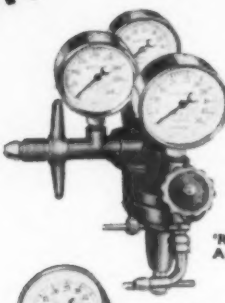
TIB. 169

'TSS' Two Stage Oxygen with Hexagon Nut Cylinder Fitting

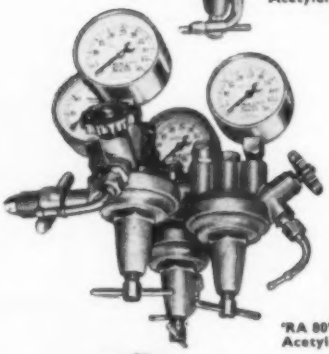
# MILNE 'Sensitive' Regulators



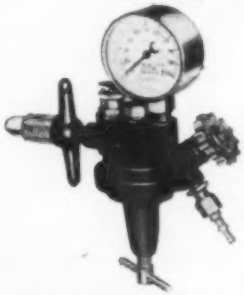
'RA 10C' Single Stage Acetylene



'RA 60' Dual Acetylene or Propane



'RA 80' Triple Acetylene or Propane



'RA' Acetylene Pipeline

(Hexagon or wing type Cylinder Nuts can be fitted to any Regulator as required)

Milne Regulators are highly accurate and are of robust construction to stand up to the wear and tear of the welding shop. Illustrated here are five of the wide range of patterns available – designed to suit every purpose where Oxygen, Air, Acetylene, Propane, Coal Gas and Hydrogen are employed.

In addition to regulators Milne manufacture Brazing, Welding and Cutting Blowpipes, Cutting and Profiling Machines, Gas Economisers, Valves for Pipe Lines and other necessary welding accessories.

To provide a comprehensive welding service to meet all the varied requirements of the Engineering and Allied Industries we can also offer Electric Arc and Resistance Welding Plant and Equipment.

*For full information and details write to:—*

## C. S. MILNE & CO. LTD.

**Manufacturers of Gas Welding and Cutting Plant and Equipment. Stockists and Suppliers of Electric Arc Resistance Welding Equipment**

Harley Works, Octavius Street, Deptford, London, S.E.8

**Telephone: Tideway 3852**

*Also at 172/174 West Regent Street, Glasgow, C.2*

MILNE

Tib 121

Then you will associate Jenkins of Rotherham with good welding. But what of Jenkins' capacity? And the co-ordination of modern fabrication techniques that quicken delivery? And inspection methods for quality control? Jenkins service covers all your requirements and additionally provides enthusiasm for new, complicated projects. Consult us and see . . .

# JENKINS *of Rotherham*

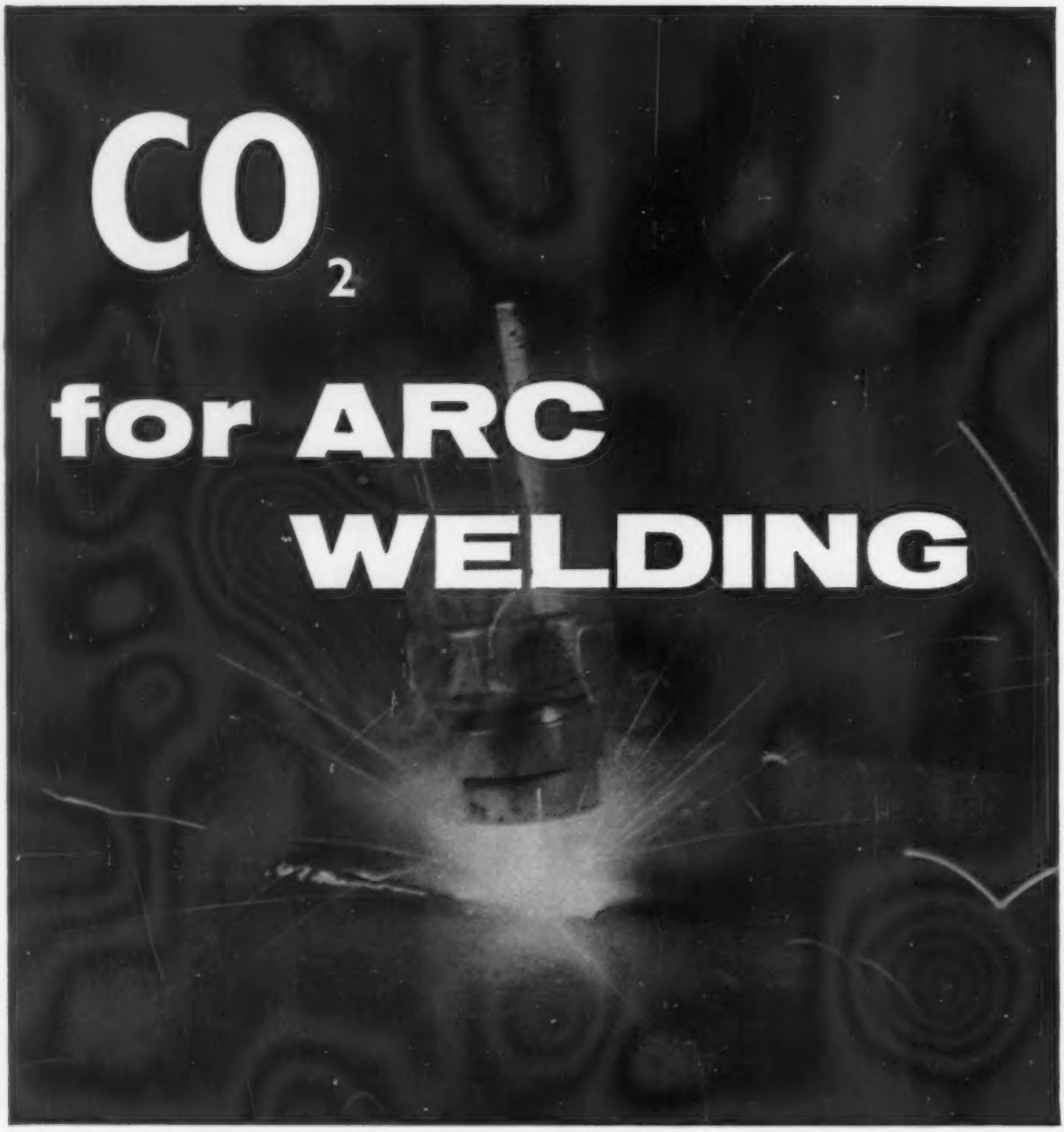
*Welded fabrication and fusion-welded pressure vessels to the requirements of Lloyds Class 1, A.S.M.E., A.O.T.C. codes and similar specifications.*

WELDED PRESSURE VESSELS IN STAINLESS STEEL, MONEL, TITANIUM, HEAVY ALUMINIUM AND MILD STEEL.

**ROBERT JENKINS & CO. LIMITED, ROTHERHAM**

*Telephone: 4201-6 (6 lines)*

THE SIGN OF GOOD WELDING




DCL

# CARBON DIOXIDE

**SUPPLY**
*Bulk Liquid, Cylinders, 'Cardice'*

**STORAGE**
*Installation, Maintenance*

THE DISTILLERS COMPANY LIMITED · CHEMICAL DIVISION
Carbon Dioxide Department · Devonshire House · Piccadilly · London · W1
Mayfair 8867

WHEN YOU ARE

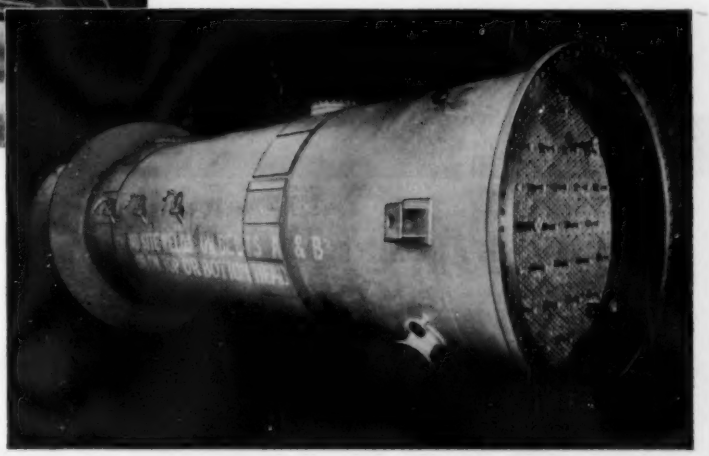
# *thinking big*

—THINK OF HARVEY

Harveys have the 'know-how', the space, the equipment and the skilled men to produce large fabricated assemblies with efficiency.
Assemblies up to 120 tons can be handled *in one piece*, and completed down to final machining. Full equipment is maintained for automatic welding, and stationary and portable X-ray units are supplemented by Radioisotopes for non-destructive testing.
Harvey engineers are always available to discuss your fabrication problems, and to advise how we can best help you.

*Left: A mild steel jacketed Autoclave to Class 1 construction with electrically driven stirring gear.*

*Below: This Ethylene Oxide Reactor weighs 135 tons, is 9 ft. 6 ins. in diameter and contains over 15 miles of 1¾ in. dia. catalyst tube.*



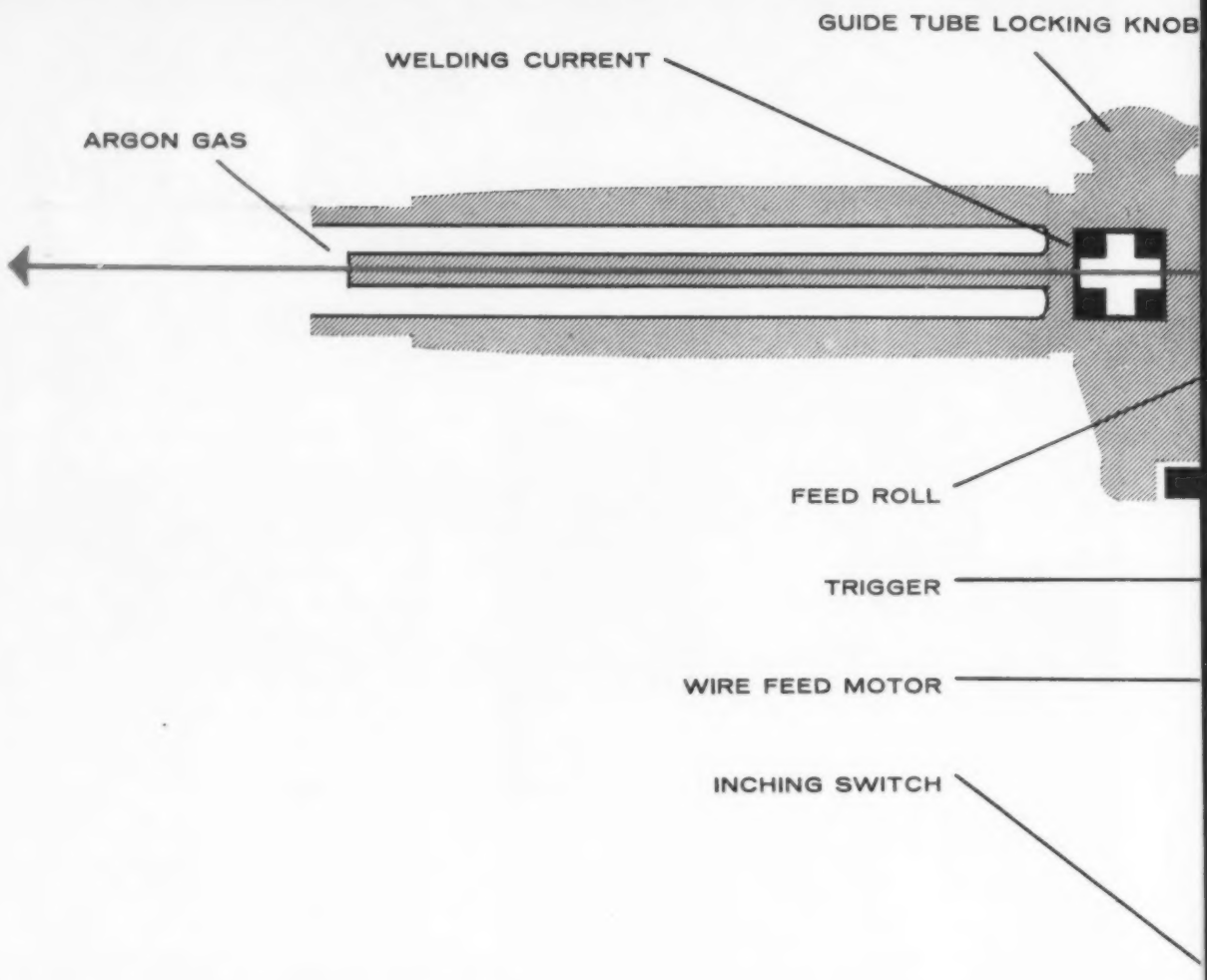
**HARVEY FACILITIES AND PRODUCTS**

CLASS I WELDED PRESSURE VESSELS TO LLOYD'S AND A.S.M.E. CODES · HEAT TREATMENT AND RADIOGRAPHY · DIE-PRESSED AND 'ROTARPREST' HEADS UP TO 15 FT. DIA. — *Larger sizes to specification* WELDED PRESSURE VESSELS AND FABRICATIONS IN ALL METALS · STEEL PLATE AND SHEET METALWORK · HEAVY MACHINING AND FITTING.

**HARVEY** FOR *large* WELDED FABRICATIONS

G. A. HARVEY & CO. (LONDON) LTD., WOOLWICH ROAD, LONDON, S.E.7. GREenwich 3232 (22 lines)

HC/HT/10



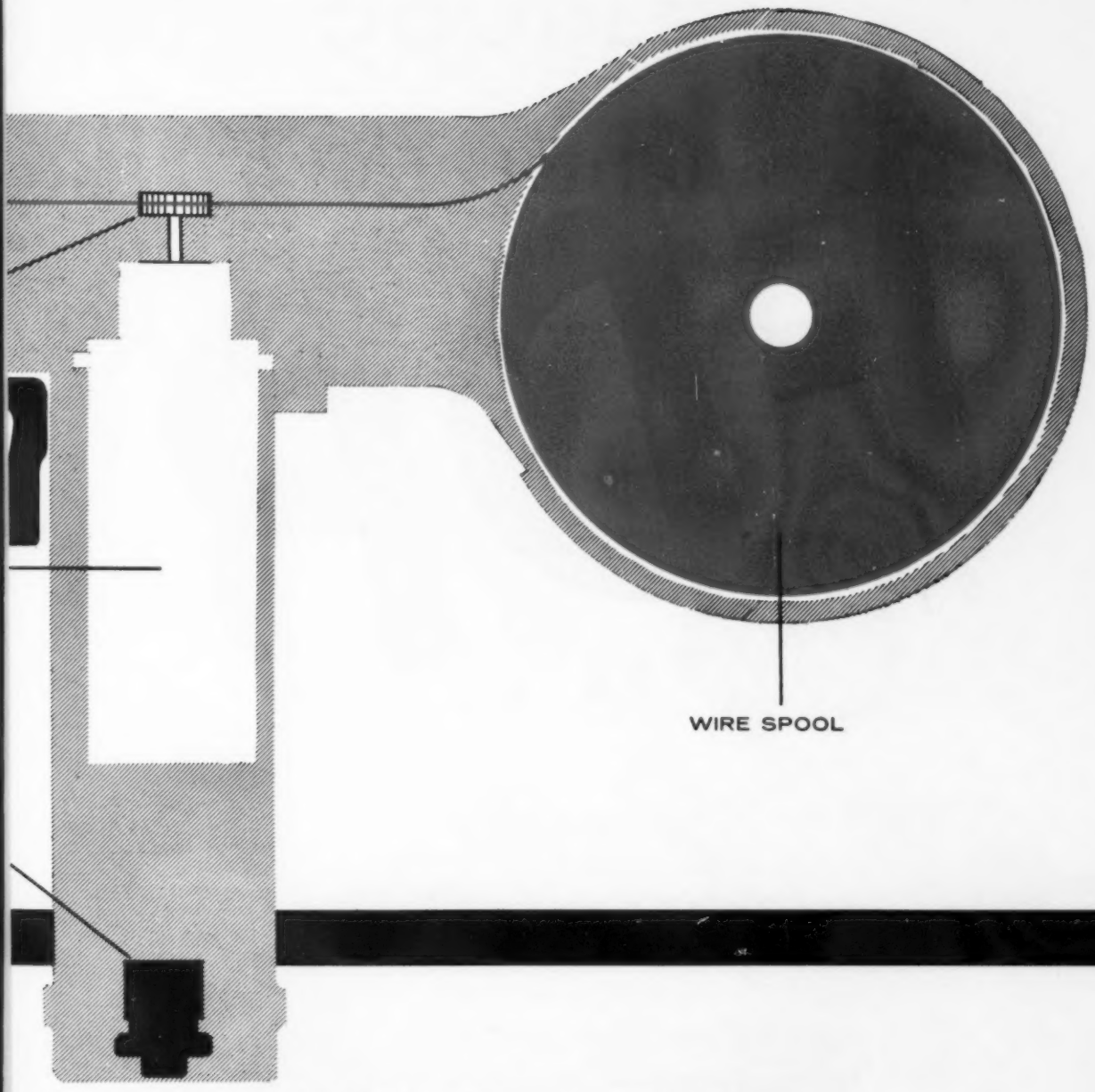

# Quasi-Arc introduce SIGMETTE

## for new ease and

SIGMETTE — Quasi-Arc's new thin-wire portable equipment brings new ease and speed of operation to welding thin-gauge aluminium and mild steel. Count its features, and you'll see how:—

- Gun is light (3 lb. 1 oz.) and well balanced for easy handling and simplicity of all-position welding.
- One standard gun covers whole range of wire sizes. (Medium speed drive motor can be changed readily for high or low speed versions to extend application range.)
- Maximum portability — gun is self-contained unit with wire spool, feed motor and trigger control.
- Uses wire from 0.030" to 1/16" in diameter.
- Once wire-feed speed has been set on control unit (supplied as standard fitting with 30 ft. leads to gun) all functions —

Quasi-Arc




# speed in thin wire welding

wire feed, argon flow, etc. — are operated by trigger on gun.
- Inching button for optimum arc striking characteristics.
- Easy maintenance — only tool needed is screwdriver.

For full technical information on SIGMETTE, write to Quasi-Arc Limited, Bilston, Staffs.

***world leaders in arc welding***

Quasi-Arc Limited, Bilston, Staffordshire

# only FIRTH-VICKERS make

# FDP

## STAINLESS STEEL

For over 25 years 'Staybrite' F.D.P. steel has been the standard material in the construction of a wide range of chemical plant. It is also used for storage and transport in the chemical, dairy and brewing industries, and is extensively applied in all types of power production.

Technical information on the use of all Firth-Vickers steels, together with technical literature are always available on request.

**FIRTH-VICKERS STAINLESS STEELS LTD., SHEFFIELD**

***is the only Company in Europe to devote its activities exclusively to the production and development of stainless and heat-resisting steels.***

# a DOUBLE event

# from British Oxygen

## Two new 7 star Single Stage Regulators

Here are two brand new single stage regulators that are ideal for heavy industry. They are the new S.O.R.1, and S.A.R.1, and they have *all* the following *7-star* features:

✱ *Simple design* ✱ *Operational efficiency* ✱ *Robust construction*
✱ *Light weight* ✱ *Easy maintenance*
✱ *Operational safety*
✱ *Low price*

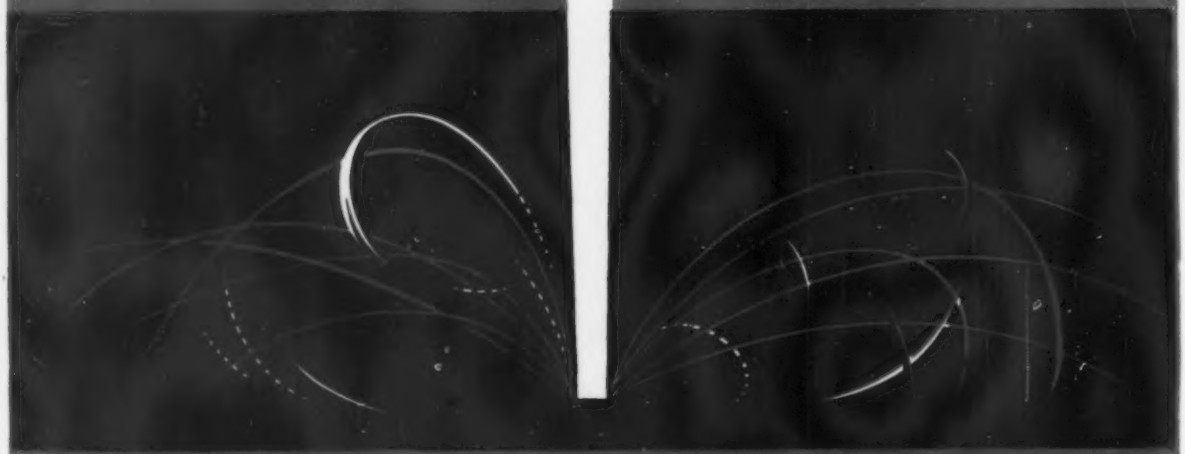
BRITISH OXYGEN GASES LTD., INDUSTRIAL DIVISION,
SPENCER HOUSE, ST. JAMES'S PLACE, LONDON, S.W.1

A BOC Company

THERE'S AN

# AEI Electrode

FOR EVERY WELDING JOB



## For downhand welding of mild steel

## the SPEEDIVICK

The ideal contact iron powder electrode.

- For long fillets, intermittent welding and butts to high radiographic standards
- Produces finely finished work quickly and easily
- Rapid burn-off rates permit high current without overheating
- Slag easily detachable or self-releasing
- Approvals include Lloyds, and the Ministry of Transport.

For full technical details write for descriptive leaflet 787/6-1

*The AEI range of 'Giant Builder' Electrodes includes*

EH · SYLVICK · MINIVICK · UNIVICK · VERTIVICK · TENSIVICK
NICHROVICK · PYROVICK · CASTIVICK · P250 · MOLVICK · LOCREEP

## Associated Electrical Industries Limited

TRANSFORMER DIVISION — HEATING & WELDING DEPARTMENT

Trafford Park - - - Manchester 17

# B·O·A·C takes good care of you —with ILFORD Industrial B X-ray film

High among the priorities of BOAC is safety. Behind the scenes at London Airport is some of the world's finest equipment, operated by highly trained personnel to ensure the reliability of every detail that contributes to safe operation.

Where even the smallest foreign particle may imperil life, nothing is left to chance. Complex units, such as engine oil coolers which cannot be dismantled for inspection, are therefore radiographically examined to detect accumulations of sludge, metal debris, and carbon particles which would spell danger if they circulated in the engine lubrication system.

For this examination, British Overseas Airways Corporation relies on ILFORD Industrial B X-ray film. Ilford has a reputation for reliability.

*Where reliability is all-important*

**ILFORD**

ILFORD LIMITED · ILFORD · ESSEX

# THE MALLORY FORMULA

$$D = \sqrt{t}$$

The formula $D = \sqrt{t}$ for the relationship between electrode tip diameter "D" and work thickness "t" was devised by MALLORY. Welding engineers the world over have adopted it as a reliable aid to efficient operation.

Material is as important as design—and here again MALLORY leadership shows itself, for the superior properties of Mallory 3 are universally recognised.

In design and in material . . . the first name is MALLORY

*Booklet 1200 "Mallory Resistance Welding" is free on request.*

**Johnson Matthey**
MALLORY

**JOHNSON, MATTHEY & CO., LIMITED**

Controlling MALLORY METALLURGICAL PRODUCTS LTD.,
**73-83 HATTON GARDEN, LONDON, E.C.1.**
**Telephone: Holborn 6989**
*Vittoria Street, Birmingham, 1. Telephone: Central 8004*
*75-79 Eyre Street, Sheffield, 1. Telephone: 29212.*

Visit THE FIRST **Engineering Materials and Design** EXHIBITION & CONFERENCE EARLS COURT LONDON 22-26 FEB 1960

W.91

**SYNTHESIS OF NEW TECHNICAL DEVELOPMENTS**

2nd - 16th JUNE 1960

# 12th

Scientific Congresses :

— International Session for Comfort in Home and City.
— International Session for Workers' Health and Safety.
— International Session on Spectroscopy.
— International Meeting of the Belgian Centre for the Study and Documentation of Waters (CEBEDEAU).
— Information Day on the industrial Applications of Atomic Energy.

# LIEGE INTERNATIONAL FAIR

*MINING*
*METALLURGY*
*ENGINEERING*
*ELECTRICITY*

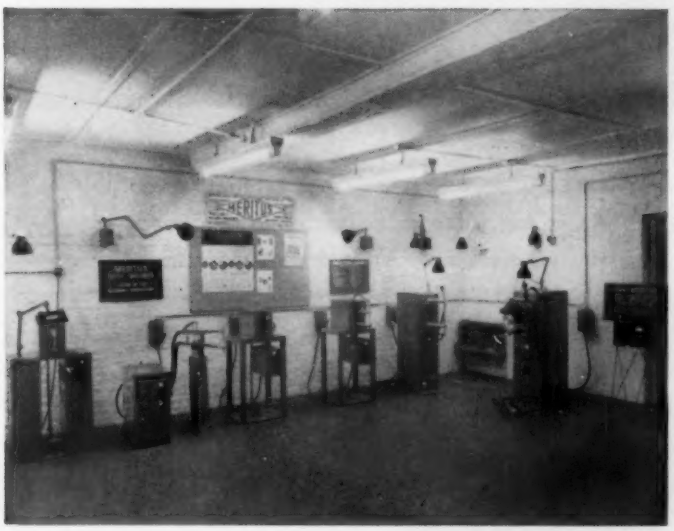
MMME

General Information :

Belgium :
Administration de la Foire Internationale de Liège,
17, boulevard d'Avroy, Liège — Tél. (04) 32.18.80.
Great Britain :
U.K. Representative, R.C. Liebman,
178, Fleet Street, London E.C.4. — Telephone : CITy 5889.

*The sessions of the International Welding Institute will be held at Liege from 13th to 18th June 1960 at the same time as the 12th International Fair of Liege.*

# RESISTANCE WELDING MACHINES




A COMPREHENSIVE RANGE OF MACHINES CAN BE SEEN
IN OUR WELDING DEMONSTRATION WORKSHOP
*WE INVITE YOUR ENQUIRIES*

## MERITUS (BARNET) LTD.

**BARNET, HERTS.** BAR. 2291/2

*Gold Medal and Bronze Medal. Brussels World Exhibition 1958. The Engineering Centre Collective Exhibit.*

What is
the cheapest
and simplest way
of fixing
this . . .

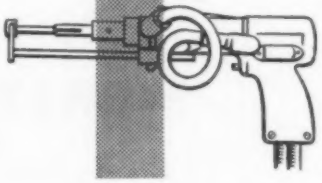
to this? . . .

When both are metal—the answer is almost invariably stud welding. The cost may be as little as one fifth of, for instance, the cost of drilling and tapping. The time an even smaller fraction. And stud welding is far stronger than any alternative method and absolutely permanent.

Stud welding is speeding up production and lowering costs in an immense range of industries from shipbuilding to domestic equipment. Attachments may be of almost any shape. A talk with our Engineers perhaps, followed by a demonstration, will be worth your while.

**Crompton Parkinson**

**STUD WELDING**



CP ELECTRICAL EQUIPMENT

CROMPTON PARKINSON (STUD WELDING) LIMITED
1-3 Brixton Road, London, S.W.9. Telephone: Reliance 7676

# Welding Titanium and Titanium Alloys

In the course of extensive research into the properties of titanium, I.C.I. Metals Division has gained considerable experience in welding the metal and its alloys.

At high temperatures, titanium rapidly absorbs embrittling elements such as hydrogen, oxygen, nitrogen and carbon. For this reason gas and metal-arc welding are not suitable, and inert-gas shielded-arc processes must be used. Most experience has so far been gained with tungsten-arc welding.

Provided that all heated surfaces are adequately shielded, titanium is one of the easiest metals to join. Unfilled welds are preferable to filled welds as it is easier to keep them free from contamination; the tip of the filler wire, if used, should always be maintained within the argon shield and the wire should be fed into the weld pool smoothly.

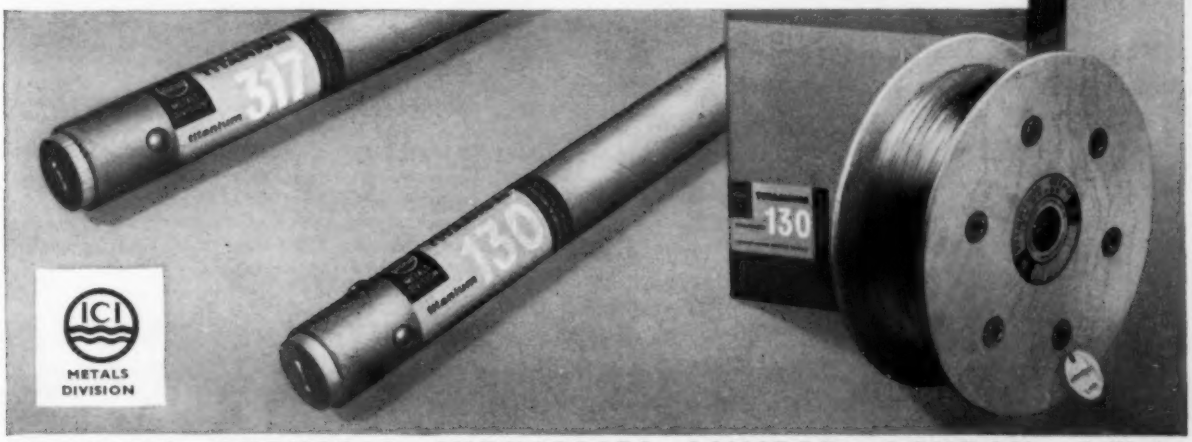
To avoid contamination and subsequent embrittlement, filler materials must be free from surface oxide and grease. Filler wire of commercial purity titanium, and of I.C.I. Titanium 317 and 230 alloy, is manufactured to high standards of quality by I.C.I. Metals Division. As it is always supplied descaled and pickled, there is no risk of contamination by the filler material provided that it is kept clean.

*Reminder!* As the Commonwealth's largest producer of wrought non-ferrous metals, I.C.I. Metals Division has built up exceptional knowledge of welding techniques. We specialise in wrought metals and alloys particularly suitable for welding and brazing—and in materials for carrying out the various welding techniques. We are always glad to help clients in selecting the most appropriate materials and processes. Please send now for our booklet 'I.C.I. Welding Rods and Brazing Materials'.

| Description | Size Range | Purpose | Process | Flux | Approximate Melting Point or Range (°C.) |
|---|---|---|---|---|---|
| I.C.I. Titanium 115<br>120<br>130 | 0.036 in. to ¼ in. diameter, in straight lengths or in 5-20 lb. coils, depending on diameter. (I.C.I. Titanium 130 also on spools for I.G.S.M.A. welding) | Welding Titanium | Argon arc | None | 1660 |
| I.C.I. Titanium 317 (5% aluminium, 2½% tin) | ⅛ in. to ¼ in. diameter or 0.080 in., 0.064 in. or 0.048 in., in straight lengths; or in coils, 3 lb. maximum weight, down to 0.036 in. | Welding I.C.I. Titanium 317 | Argon arc | None | 1590 |
| I.C.I. Titanium 230 (2% copper) | ditto | Welding I.C.I. Titanium 230 | Argon arc | None | 1610-1640 |

## Quick delivery

*We make a very large range of welding and brazing rods and orders for many standard lines can be filled from stock. Your nearest I.C.I. SALES OFFICE will ensure that you get prompt delivery of any materials ordered.*




ICI METALS DIVISION

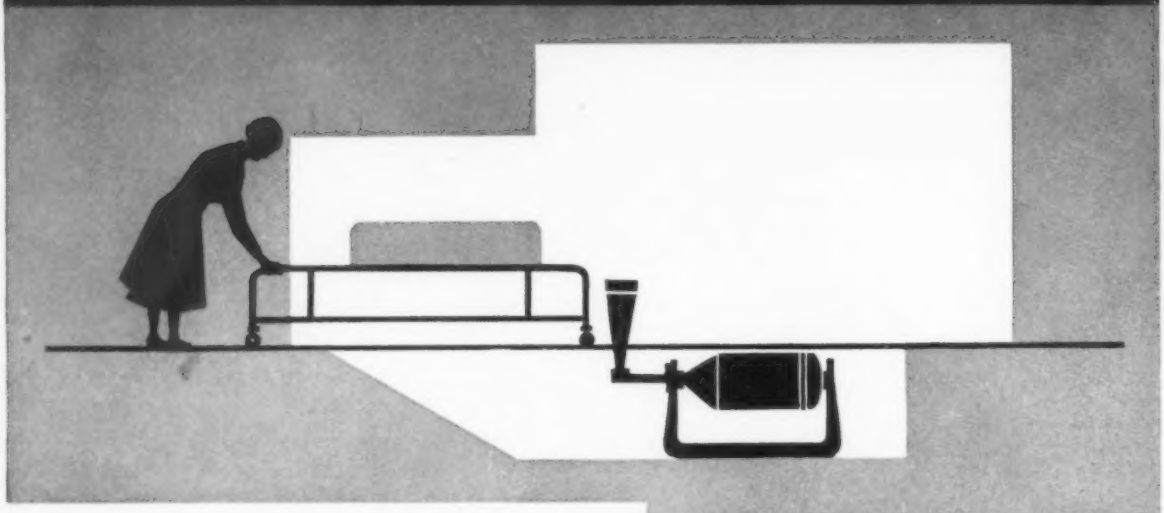
IMPERIAL CHEMICAL INDUSTRIES LIMITED, LONDON, S.W.1

M.29

# Right to the job

at the

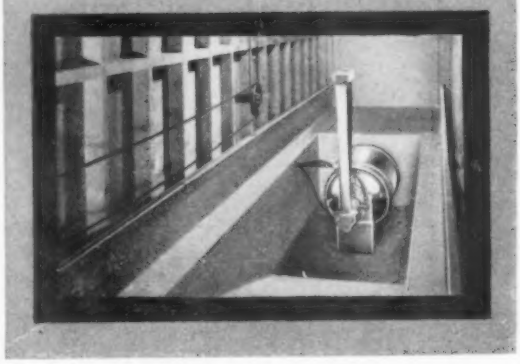
ROYAL ORDNANCE FACTORY PATRICROFT



The LIGHTWEIGHT

## RAYMAX 150

Here, five Raymax 150 units make an impressive and economic testing installation at the R.O.F. Patricroft. Components are tested in narrow space-saving leadply tunnels right on the factory floor. When examining longitudinal joints the component on the trolley is moved down the tunnel by means of a simple chain drive worked externally by the radiographer. As shown in the illustrations, the Raymax 150 is sunk in a pit thereby simplifying the protective measures necessary as the beam is always directed upwards against the roof of the tunnel.



*In this installation the use of leadply tunnels only 4 ft. wide, instead of larger radiographic rooms, enables a considerable saving to be achieved in costly protective materials, in floor space and in time as the components do not have to be taken away from the shop floor. The gas-insulated Raymax 150 weighs only half conventional oil-insulated units. It gives high radiographic output, and its special design eliminates high voltage cables, rectifying valves and associated filament transformers.*

*Write for publication SP.7176/1*
*to your local AEI office or direct to:*

**Associated Electrical Industries Limited**

**INSTRUMENTATION DIVISION – Scientific Apparatus and X-Ray Department**
**132/135 Long Acre, London. W.C.2.**

# the SATURN-HIVOLT

## Surge Injector Argon Arc Welding Unit Mk. 1a

**permits welding up to 300 amps**

This specially developed machine is now being used extensively in Industry. It is rugged in construction and has clearly defined fully automatic controls. The arc is stable and starts from cold. Enables any normal single-operator welding transformer, having an open circuit voltage of between 40 volts and 110 volts, to be converted at will into an efficient Argon Arc Welding Unit. Compact in size, the machine measures 30" high by 25" wide and 28" long, and is mounted on castors.

A demonstration of this machine, or of our other models Mk. II and Mk. III, (output up to 600 amps.) will gladly be given in your own factory.

**CONTRACTORS TO:**

*Admiralty, Air Ministry,*
*Ministry of Supply, U.K. Atomic Energy Authority,*
*Australian Atomic Energy Authority.*

## SATURN INDUSTRIAL GASES LIMITED

**Gordon Road, Southall, Middlesex. Phone: Southall 5611**

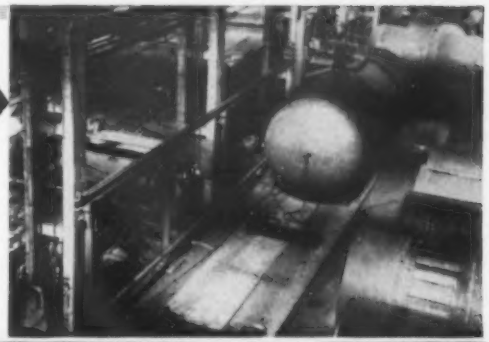
Branches: GLASGOW ALDRIDGE BIRMINGHAM MANCHESTER
SHEFFIELD LYMINGTON SUNDERLAND THORNABY-ON-TEES

# A WORLD OF WELDING EXPERIENCE...

*The headquarters of the Baker Perkins Group at Peterborough*

**This Yates equipment is designed to save labour and produce better quality work. It is proving itself daily in many of our leading fabrication shops.**

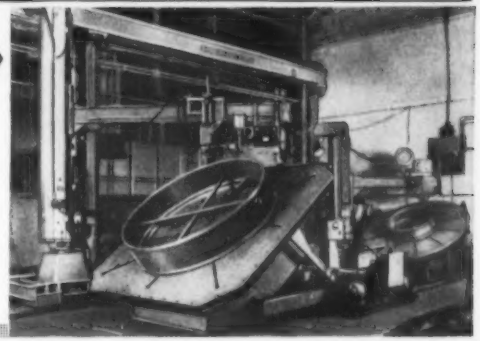
Showing complete typical automatic Class 1 Welding installation, comprising 4-20 ton rotators and travelling elevating welders, platform. The operator has fingertip control for rotating vessels and positioning welding head. Photo by courtesy of G. A. Harvey & Co. (London) Ltd.



**YATES PLANT LIMITED**

Designers and manufacturers of all types and capacities of Manipulators, Rotators, etc., including fully automatic welding installations.

Photo by courtesy of Fluidrive Engineering Co. Ltd. Two Yates patented Travelling Columns with elevating and Rotating Welding Booms operating over two of our standard Rocking Manipulators, which are built in 3 to 50 ton capacities. The work tables of the Manipulators have an infinitely variable speed rotation and can be tilted from the horizontal to 90°. By this ingenious design the weight of the work piece assists tilting and obviates the necessity of heavy gearing.



**A MEMBER OF THE BAKER PERKINS GROUP OF COMPANIES**

**All Yates equipment is now manufactured by BAKER PERKINS LIMITED in their modern well equipped factory at Hebburn-on-Tyne where they are 'tooled' to meet all demands.**

**YATES PLANT LTD** A MEMBER OF THE BAKER PERKINS GROUP **WHIDBORNE STREET, LONDON W.C.1.** *Tel: Terminus 0842 and 0568*

YP/IA

# THE INSTITUTE OF WELDING

54 Princes Gate, London, S.W.7

◆

## COUNCIL and OFFICERS

**PRESIDENT**

E. Seymour-Semper

**VICE-PRESIDENTS**

W. Barr, O.B.E. E. Fuchs
G. Roberts

**PAST-PRESIDENT**

J. Strong

**HONORARY TREASURER**

W. E. Harriss

**Chairman of Executive Committee:** R. E. G. Weddell

**Representatives of Industrial Corporate Members**

E. F. Burford, M.B.E.
C. Humphrey Davy
N. L. G. Lingwood
J. A. McWilliam, T.D.
E. S. Waddington
Dr. R. Weck

**Representatives of Fellows, Members, and Associate Members**

D. J. W. Boag
V. W. Clack
F. Clark, M.B.E.
D. C. C. Dixon
J. A. Dorrat
E. Flintham
E. P. S. Gardner
S. H. Griffiths
Dr. N. Gross
D. B. Kimber, O.B.E.
T. McIver
H. Martin

**Representative of Companions**

J. Hooper

**Representative of Associates**

A. Evitts

**Chairman of B.W.R.A. Council:** A. Robert Jenkins, J.P.

**Chairmen of Standing Committees**

| | |
|---|---|
| Education Committee | Prof. J. G. Ball |
| Finance Committee | W. E. Harriss |
| Membership Committee | R. G. Braithwaite |
| Programme and Publications Committee | J. F. Lancaster |
| School of Welding Technology Committee | E. Fuchs |
| Technical Committee | J. A. Dorrat |

**Representatives of Branches**

| | |
|---|---|
| Birmingham | W. R. Harper |
| East Midlands | A. E. Harrison |
| East of Scotland | J. F. Wheeldon |
| Eastern Counties | J. Edwards |
| Leeds | E. Rose |
| Liverpool | G. A. O. Pridgeon |
| Manchester | J. M. Whitworth |
| North Eastern (Tees-side) | J. W. Jackson |
| North Eastern (Tyneside) | R. A. Exton |
| North London | C. R. Thatcher<br>L. C. Percival |
| Preston | F. Pilling |
| Sheffield | W. A. Jenkins, J.P. |
| Southern Counties | J. H. Gillespie |
| South London | Dr. M. C. Nickson |
| South Wales | I. B. Ford |
| South Western | A. J. Francis |
| West of Scotland | J. E. Roberts |
| Wolverhampton | M. R. Liddiatt |

**SECRETARY**

G. Parsloe

# BRITISH WELDING RESEARCH ASSOCIATION

29 Park Crescent, London, W.1

◆

## COUNCIL and RESEARCH BOARD

**PRESIDENT**

Sir Charles S. Lillicrap, K.C.B., M.B.E.

**CHAIRMAN OF COUNCIL**

A. Robert Jenkins, J.P.

**HONORARY TREASURER**

W. E. Harriss

**Members of Council**

Sir Donald Bailey, O.B.E., J.P.
Prof. J. F. Baker, O.B.E., F.R.S.
Dr. R. Beeching
D. J. W. Boag
J. Brown
Dr. T. W. F. Brown, C.B.E.
C. Humphrey Davy
C. H. Flurscheim
T. M. Herbert
E. J. Hill
F. C. S. L. Lewin-Harris
H. Pearson Lobnitz
Sir Andrew McCance, F.R.S.
Richard Miles
J. Mitchell, C.B.E.
Prof. Sir Alfred Pugsley, O.B.E., F.R.S.
L. Rotherham
E. Seymour-Semper
R. B. Shepheard, C.B.E.
C. M. Spielman, O.B.E., M.C.
T. Stevenson
J. H. N. Thompson, M.C.
Lt.-Col. J. F. Todhunter
W. T. Towler, J.P.
Dr. M. A. Vernon
Dr. E. G. West
J. M. Willey

**Research Board**

Dr. E. G. West (*Chairman*)
Dr. N. P. Allen, F.R.S.
Prof. G. Wesley Austin, O.B.E.
Prof. J. G. Ball
W. Barr, O.B.E.
Dr. L. E. Benson
Dr. J. S. Blair
Dr. N. Booth
E. Fuchs
E. P. S. Gardner
A. H. Goodger
Dr. Nicol Gross
Dr. H. K. Hardy
Dr. H. Harris
A. Robert Jenkins, J.P.
Dr. N. J. L. Megson
Sir Charles Lillicrap, K.C.B., M.B.E., D.S.C.
Dr. W. I. Pumphrey
Dr. L. Reeve
G. Roberts
Prof. E. C. Rollason
Dr. H. Sutton, C.B.E.
J. Turnbull
Dr. J. H. Weaving

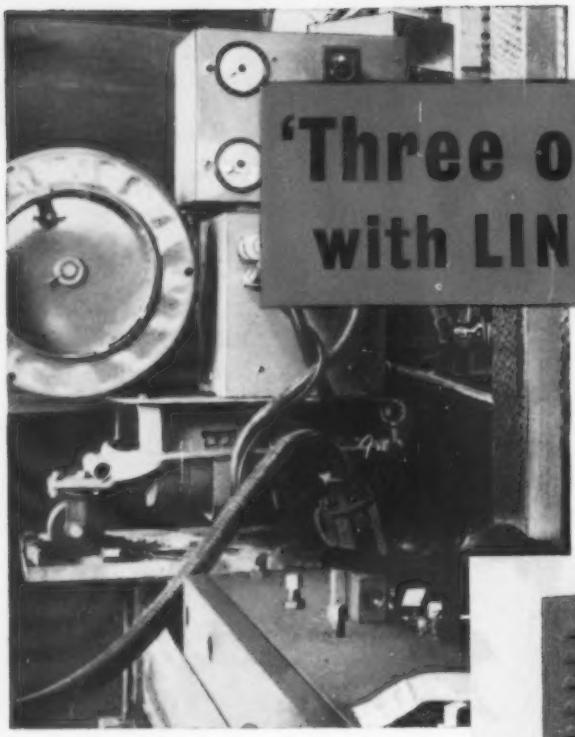
**DIRECTOR OF RESEARCH**

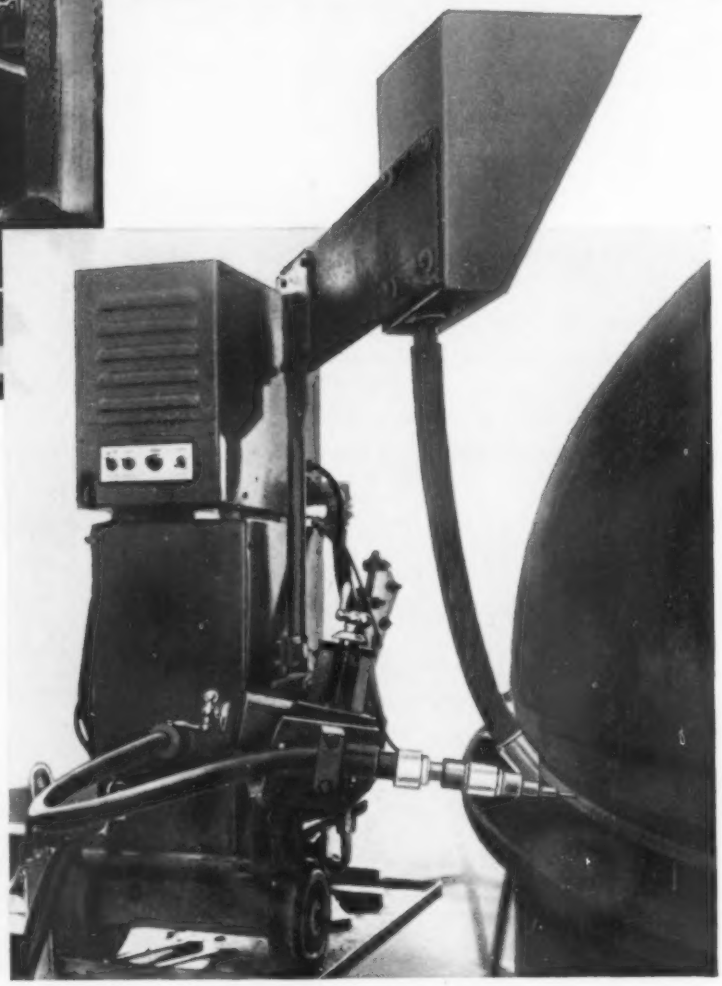
Dr. Richard Weck

**SECRETARY**

A. O'Neill

# 'Three o'clock' welding with LINCOLNWELD





THE LINCOLNWELD Universal Tractor in action at the Derby works of International Combustion Co. Ltd. The illustrations show the Universal Tractor automatically welding in the '3 o'clock' position, a section of one of 4 heat exchangers for The Advanced Gas Cooled Reactor, being built at Windscale, Cumberland, for the United Kingdom Atomic Energy Authority. (Photographs by the courtesy of International Combustion Co. Ltd. and U.K.A.E.A.

Butt welding, Fillet welding, Lap welding and now horizontal/vertical '3 o'clock' welding—all are possible with the latest LINCOLNWELD UNIVERSAL TRACTOR Submerged Arc Welding Unit.

Don't spend money-make money with LINCOLNWELD! For further details of how Lincolnweld extra versatility can help you solve your welding problems, please write to:

GKN

*The Automatic Division*

**LINCOLN ELECTRIC COMPANY LIMITED**

**WELWYN GARDEN CITY · HERTS · ENGLAND · Telephone: WELWYN GARDEN 920/4 · 4581/5**

UTI

# BRITISH WELDING JOURNAL

OFFICIAL JOURNAL OF THE INSTITUTE OF WELDING AND THE BRITISH WELDING RESEARCH ASSOCIATION

Incorporating the *TRANSACTIONS* of the Institute and *WELDING RESEARCH*

## CONTENTS

INSTITUTE OF WELDING

*Arc Physics Conference*

71 **The Electric Arc in Welding: Introductory Survey**
*By E. C. Rollason*

73 **Arc Characteristics and their Significance in Welding**
*By D. R. Milner, G. R. Salter, and J. B. Wilkinson*

89 **Gas Absorption from Arc Atmospheres**
*By G. R. Salter and D. R. Milner*

101 **Metal Transfer in Inert-Gas Shielded-Arc Welding**
*By J. C. Needham, C. J. Cooksey, and D. R. Milner*

115 **Heat Transfer from Arcs**
*By J. B. Wilkinson and D. R. Milner*

BRITISH WELDING RESEARCH ASSOCIATION

129 **Effect of Arsenic on the Weldability and Notch Toughness of Mild Steel to API Grade B Specification**

141 NEWS AND ANNOUNCEMENTS

145 CURRENT WELDING LITERATURE

**FEBRUARY 1960**
**Volume 7 Number 2**

*Subscriptions*
Members free:
Extra copies at 7*s.* 6*d.* each
Non-Members:
£5 per annum
Single copies 10*s.* each

*Published Monthly*

*Editor-in-Chief:* G. PARSLOE, M.A.
54 Princes Gate, London, S.W.7
(Knightsbridge 8556)

*Executive Editor:*
C. ROWLAND HARMAN, B.Sc. (Eng.)
Editech
6 Ridge End, Hook Hill Lane
Woking, Surrey
(Woking 2981)

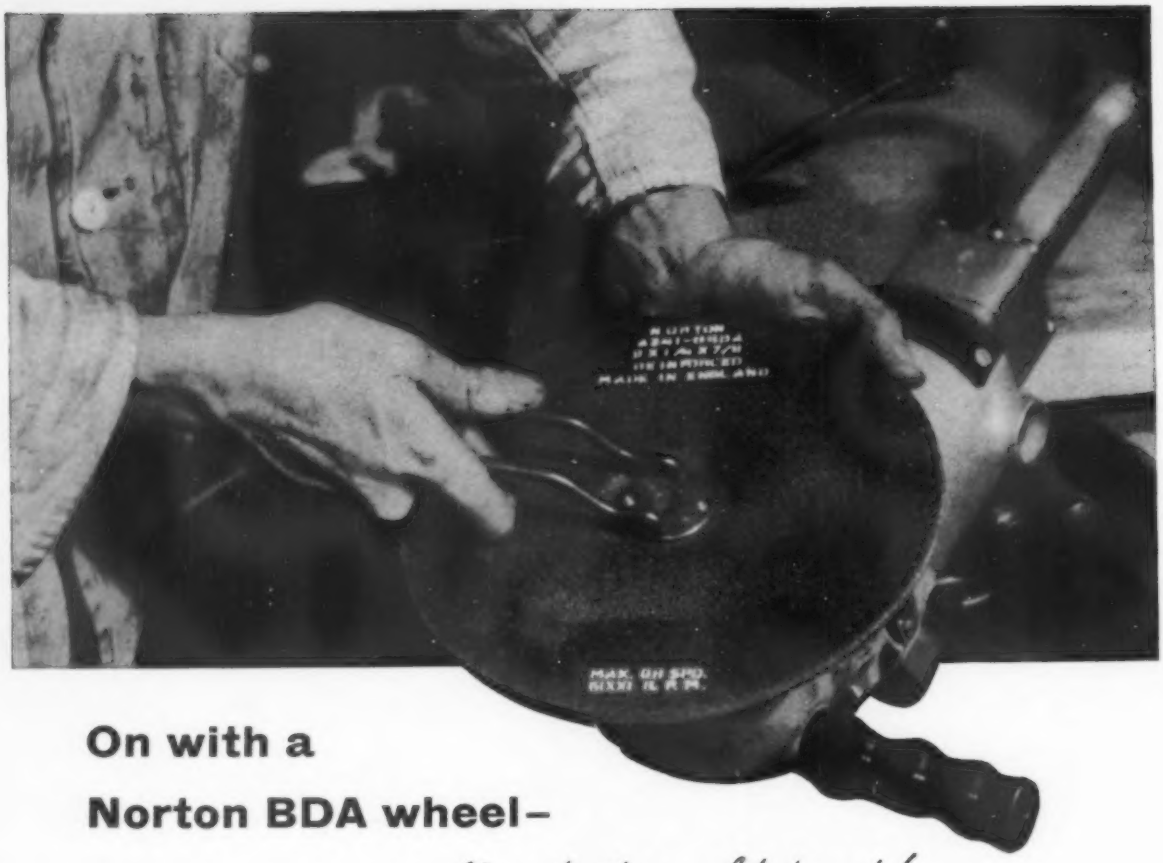
*Advertisement Manager:*
G. S. HARTLEY,
54 Princes Gate, London, S.W.7.
(Knightsbridge 8556).

*Note:* Editorial contents copyright. The Institute of Welding and the British Welding Research Association do not hold themselves responsible for statements made or opinions expressed in articles appearing in this Journal.

---

**The Institute of Welding** 54 Princes Gate, London S.W.7

**British Welding Research Association** 29 Park Crescent, London W.1



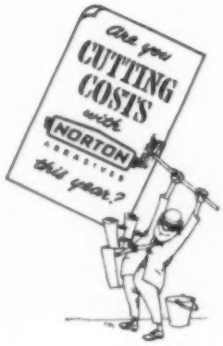
# On with a Norton BDA wheel–

## *off with the weld bead!*

This 9" x ¼" x ⅞" depressed centre wheel is a Norton A241-QBDA reinforced resinoid wheel. It is mounted and ready now to cut into its work with speed *and* safety, because it is doubly reinforced with a strong integral fabric and a tough nylon safety web.

They're versatile, these Norton BDA Reinforced Wheels. Use them for cleaning up, bevelling, cutting down, and smoothing (for cutting-off specify the thinner BD type). Roughing and finishing, tough Norton Reinforced Wheels will do a sturdy job–and do it with the utmost speed and economy.

*In the Norton range of wheels—over 100,000 sizes, shapes and specifications—there is one that is exactly right for your job. Let your Norton or Alfred Herbert representative help you select it, and if you want it for weld grinding, cleaning up and the multitude of jobs you do with your portable right-angle grinder, it will probably be a Norton BDA or BD reinforced resinoid wheel.*




## *Get through more work with Norton Abrasives*

*NORTON ABRASIVES

**NORTON GRINDING WHEEL COMPANY LIMITED**

Welwyn Garden City, Herts. Telephone: Welwyn Garden 3484 (15 lines)

Enquiries also to: **ALFRED HERBERT LIMITED, Coventry** · Telephone: Coventry 89221

*NORTON and BEHR-MANNING factories also in Argentina, Australia, Brazil, Canada, France, Germany, Italy, Northern Ireland, South Africa and U.S.A.*

**Regd. Trade Mark of Norton Grinding Wheel Co. Ltd.*

N.G.W. BDA. 158

JOINING OF METALS CONFERENCE

# The Electric Arc in Welding

*A conference on this subject was organized by the Department of Industrial Metallurgy at the University of Birmingham, on 25th June 1959, under the Chairmanship of Professor E. C. Rollason. The papers presented at the Conference were: (1) Opening Address and "Introductory Survey", by Professor E. C. Rollason; (2) "A Survey of Arc Characteristics and their Significance in Welding", by D. R. Milner (Birmingham University Joining of Metals Team); (3) "Gas Absorption from Arc Atmospheres", by Dr. G. R. Salter (Birmingham University Research Team); (4) "The Mechanism of Metal Transfer in the Welding Arc". by J. C. Needham (Electrical Research Association); (5) "Heat Transfer from Arcs". by J. B. Wilkinson (Birmingham University Research Team); (6) "Plasma Projectors and Constricted Arc Torches—their Design, Characteristics and Application",* by A. R. Moss (Ministry of Supply Armament Research and Development Establishment).*

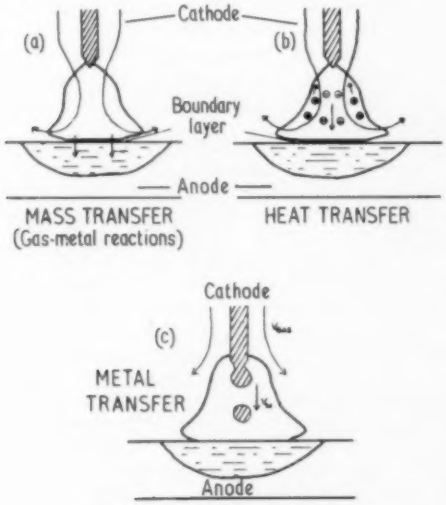
## INTRODUCTORY SURVEY

*By E. C. Rollason*, M.SC., PH.D., F.I.M., M.INST.W.

IN the Department of Industrial Metallurgy of Birmingham University an active research team has been working on brazing, pressure welding, and arc welding problems. Not unnaturally, the approach to the problems is academic with the main object of finding the principles underlying the various processes, but to promote an exchange of ideas with other workers in academic and industrial circles occasional conferences are organized.

The subject of this third conference is "The Electric Arc in Welding". The arc welding of metals is now a well established process as a result of empirical development from 1890 onwards. The second world war, however, provided a considerable impetus to progress by expediting the development of the inert-gas-shield process, from which followed the consumable-electrode gas-shielded processes which have greatly extended the arc welding of metals. Developments are still going on to find processes for the welding of the reactive new metals, to weld thicker sections and to adapt the constricted arc for cutting, welding, and spraying.

Numerous features of these practical developments are still defined in an empirical manner because fundamental work on the subjects is made difficult by the complexity of the variables involved. The introduction of the inert-gas shielded-arc welding process, however, makes it easier to design experiments which isolate the individual parameters and thus allow interpretation of the results to be less ambiguous.




1—*Modes of transfer in the metal arc*

### Fundamentals of Arc Welding

Underlying the development of arc welding are four main problems:

(i) *Heat Transfer*. The use of the arc as a source of heat for the formation of the weld pool and the melting of the electrode (see Fig. 1).

(ii) *Mass-transfer*. The intense chemico-metallurgical reactions which take place between the high-temperature gases in the arc atmosphere and the molten drops or pool, *i.e.*, mass movement of active gases from the arc atmosphere to the metal

(iii) *Metal transfer*. The mechanism of metal drop transfer in consumable electrode welding

(iv) *Arc Stability*. The study of the initiation and maintenance of the welding arc to enable suitable power sources and

Manuscript received 20th October, 1959.

Professor Rollason is Head of the Department of Industrial Metallurgy at Birmingham University.

* Restricted report, not available for publication.

associated equipment to be designed. This aspect is not discussed at this conference.

**Heat Source**

The primary use of the arc is as a source of heat which creates a high temperature zone of intense chemical activity and which also melts the plate and the electrode. The heat is imparted to the metal in two ways: firstly, by way of the energy and heat of condensation of the stream of electrons entering the anode; and secondly by conduction and convection from the arc column.

To be able to analyse the formation of the weld pool it is necessary to know the proportions of total heat which enter the electrodes. Further, the temperature distribution in the arc atmosphere and in the immediately adjacent metal affects the distribution and composition of the reacting constituents and hence the chemico-metallurgical reactions occurring between the gas and the metal. Consequently, in considering the problem it is necessary to know the distribution of heat dissipation and the temperatures attained in the arc zone.

Several workers have made calorimetric measurements of the distribution of the heat dissipated in the arc, but attempts to relate these results with the mechanism of the arc have not led to any coherent understanding of the processes occurring. In particular, little has been done to sort out the relative contributions to the heat input to the pool of (*a*) the electron stream, and (*b*) heat transfer from the arc column. Earlier work by the Birmingham team suggests that only the electron heating is useful in forming the weld pool, whereas one might expect that it is the movement of the hot gas from the arc column which determines the chemical reactivity.

**Chemical reactivity**

The problems of chemical reactivity in arc atmospheres and heat transfer from the arc column to the weld plate have much in common.

For reactivity or mass transfer, cold molecules of gas from the surrounding atmosphere feed into the arc column, where they are dissociated to form highly active atomic gas which reacts with the molten metal, whereas in heat transfer cold molecules or atoms are heated up in the arc and impinge on the anode to impart part of their energy as heat to the anode. This underlying similarity has led the team at Birmingham to carry out two investigations.

Firstly, a simple reaction has been investigated to determine the factors of significance—this was the work on oxygen absorption in titanium. This system was chosen not because of interest in titanium but because experimentally it provided the basic data required for the simple case of a metal absorbing all the oxygen available in the arc atmosphere. The increase in hardness was a simple test for indicating the amount of oxygen absorbed.

Secondly, a supplementary investigation is being made of the heat transfer from the arc to the weld plate, with attempts to separate the electron heating and the column heating.

The general conclusion is that in both cases the mechanism is the same; in the arc the gas is highly turbulent, but adjacent to the molten pool it is nearly stationary and it is diffusion across the so-called 'stagnant boundary layer' adjacent to the molten metal which controls the gas-metal interaction.

In this type of problem the gas flow conditions are very important, and for some time the team could not understand why it was that when the gas-flow pattern was modified, for example by changing the flow rate in the torch, the mass transfer and heat transfer did not alter in the way it should. In the course of seeking an answer to this problem some recent German work on plasma theory and arc physics was discovered in which it was shown that as a result of electromagnetic forces, *i.e.*, a pinch effect acting on the gas in the arc, the arc was caused to act as a pump setting up gas jets with velocities of the order of $10^4$ cm/sec as compared with $10^2$ cm/sec for the average flow rate. The presence of such jets in argonarc welding was sought and found, and it was concluded that it is these gas jets which control the rate of heat and mass transfer inasmuch as the gas-flow pattern is significant.

**Metal Transfer**

It was then realized that these gas jets were probably the cause of metal transfer, and an experimental and theoretical research was initiated to investigate the possibility. The measurement of the velocities attained by the globules of metal as they are transferred across the arc, and comparison with simple calculations on the forces and consequent velocities obtainable from the plasma jets, showed this to be very promising. It was then found that the E.R.A. were also conducting an investigation into metal transfer having much the same mechanism in view but using a totally different experimental technique. Since in many ways the two investigations were complementary, forces were joined and this resulted in the work on metal transfer to be presented today.

The problems of heat, mass, and metal transfer have been with us since the beginning of arc welding, but a new 'slant' has been introduced by the application of the constricted arc to welding and cutting processes. The fact that constricting an electric arc by burning it in a narrow cooled passage resulted in a high-temperature plasma jet was first discovered in 1922, but it is only recently that this principle has found technological application. Thus, as well as being interested in heat transfer in arcs in general, the Birmingham team now have a particular interest in the effects of constricting the arc.

We therefore have five papers today. The first of these presented by Milner gives the background knowledge of those aspects of the mechanism of the electric arc which are relevant to problems occurring in welding. The second and fourth by Salter and Wilkinson deal with mass and heat transfer respectively, and describe the results of experiments which have been carried out by the Birmingham team and relate the results as far as is possible to the conditions existing in the arc. The third joint paper by Needham presents the results of experimental and theoretical work carried out at E.R.A. and at Birmingham on metal transfer, showing how this is brought about by the plasma jets mentioned earlier. Finally there is a paper by Moss which represents the emphasis now being given to the constricted arc and its possible applications to metallurgical processes.

# ARC CHARACTERISTICS

## and their Significance in Welding

*By D. R. Milner,*
*G. R. Salter,*
*and J. B. Wilkinson*

*A survey is made of those aspects of arc physics which relate to the chemico-metallurgical reactions occurring between the arc atmosphere and the weld metal, heat transfer from the arc, and metal transfer in consumable electrode welding. The energy balance for the arc column plays an important part in these arc-metal interactions and has been established for arcs in which heat is transferred by conduction only. This shows that, above a critical current determined by the dissociation of molecular gases and ionization of atomic gases, arcs develop inner cores. Other modes of heat transfer play a part in the welding arc and in this respect plasma jets are very important. Plasma jets with a velocity of the order of $10^4$ cm/sec occur wherever an arc is constricted* (e.g., *by the cathode spot in tungsten arc welding and when welding with a small gauge electrode*) *and becomes more intense when the inner core develops. These jets are probably important in welding in many ways,* e.g., *in transporting reactive gases to the weld pool, in heat transfer from the arc column, in crater formation, in metal transfer from the arc, and in determining the effectiveness of gas shrouding.*

*Cooling and constricting an arc increases the core temperature, since the smaller conducting area has to attain a higher conductivity to maintain the current. If the arc is cooled and constricted by gas flowing along its length the issuing high-velocity, high-temperature plasma jet can be utilized for the welding, cutting, and spraying of metals.*

*The heat input to the anode, which is related to the anode drop, determines the formation of the weld pool in straight polarity welding and the melting of the electrode in reverse polarity welding. Recent researches in arc physics suggest that the anode drop is not constant, as has hitherto been assumed, but varies with both arc length and current. The magnitude of the anode drop is related to the presence of cathode plasma jets, anode plasma jets, the positive and negative ion supply from the anode, and the anode plasma temperature.*

*On the subject of the cathode drop region, arc physics has remained relatively static because of the extreme conditions which exist there, and little fundamental knowledge is as yet available for application to welding systems.*

### Introduction

THE purpose of this paper is to survey the present state of knowledge of arc physics, giving particular emphasis to those aspects which appear to be of importance in arc welding. It is first necessary to decide which features in the formation of a weld are related to processes occurring in the arc, and this has been done in the introductory paper to this series by Professor Rollason, who postulated the classification of the pertinent problems under the following four headings:

(i) The primary use of the arc as a source of heat for the formation of the weld pool and the melting of the electrode

(ii) The study of the characteristics of the arc as a circuit element, so that power sources and associated equipment can be designed to initiate and maintain a stable arc

(iii) Chemico-metallurgical reactions which take place between the metal electrodes and the high-temperature gases in the arc atmosphere and which often result in embrittlement or porosity of the weld

(iv) The mechanism of metal transfer in consumable electrode welding.

The second of these problems, *i.e.*, the initiation and maintenance of the welding arc is being treated in a series of articles by Orton and Needham[1] reporting work carried out at the Electrical Research Association, and will not therefore be considered in the present paper. The other three problems are all concerned with interactions between the metal electrodes and the arc, and it is necessary that they should be related to the processes occurring within the arc so that those aspects of arc physics which are relevant can be specified.

The function of the arc as a source of heat requires an understanding of the overall conversion of electrical energy into heat in the arc and of the proportion of this heat which enters the electrodes. The chemico-metallurgical reactions taking place between the gas and the

Manuscript received 3rd October, 1959.
The authors are in the Department of Industrial Metallurgy at Birmingham University.

metal depend on the distribution and composition of the reacting constituents, which in turn is determined by the temperature distribution in the arc atmosphere and in the immediately adjacent metal, as well as the pattern of the gas flow which transports the reacting gas to the metal surface. Metal transfer must depend upon the existence of forces in the arc which, although electrical in origin, are able to exert a mechanical effect on the globules of metal transferred from the melting electrode to the weld pool. That such forces exist has been known for a long time, and some measurements have been made of their magnitude. It was not until 1955, however, that Maecker[2] demonstrated the origin of these forces and of the plasma jets associated with them. As a result of this work it has now become possible to develop a theory of metal transfer which is described in a paper in the present series (*see* p. 101). In addition to discussing the three arc/metal interactions which are basic to welding, a section has been included treating the effect of constricting an arc, in view of the current interest in this subject.

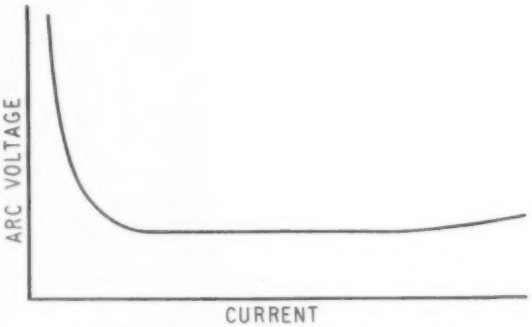
It was realized many years ago that if the arc column could be constricted its temperature would be very much increased, and the first successful experiments in this direction were carried out in 1922.[3] Since then constricted arcs have been utilized by spectroscopists to produce arc temperatures up to 50,000°C.; while within the last few years attempts have been made to apply the constricted arc commercially, the most successful application to date being the cutting of a wide range of metals and alloys.

The electric arc has been the subject of a large number of fundamental investigations, as a result of which some principles of arc behaviour have been established, although much has yet to be done to elucidate the detailed processes occurring within the arc. However, it is necessary to use care when applying these principles of arc physics to welding systems, since fundamental research has been concerned primarily with the carbon arc in air, and with mercury and xenon arcs, at considerably lower currents than those generally used in welding. The authors do not know of any detailed investigation of the arc in an actual welding system. The most pertinent work was that of Busz-Peuckert and Finkelnburg who investigated a system similar to that used in argonarc welding, in which the arc was operated between a tungsten cathode and a copper anode in an atmosphere of argon;[4, 5, 6, 7] but the copper anode was solid, being water cooled, and this may be the reason why some of the results obtained do not agree with observations from welding practice.

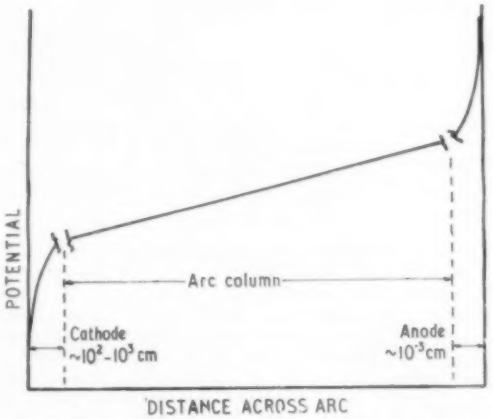
The present state of knowledge of the fundamentals of arc physics has been admirably reviewed in an article by Finkelnburg and Maecker[8] to which this present paper is much indebted. The information available from the welding field to 1942, together with some of the fundamental work, was described in a review paper by Spraragen and Lenguel.[9] The present survey has, therefore, been limited to an attempt to establish the fundamental processes underlying the three aspects of arc/metal interactions outlined in the introduction. The more important arc phenomena in this respect are the energy balances at the electrodes, the conversion of energy to produce gas at high temperature in the arc atmosphere, the movement of gases in the arc, and the forces acting on the electrodes.

## Mechanism of the Electric Arc

An arc exists as the result of the passage of electricity through a gas between two electrodes, and it can be formed only under conditions where the continuity of current can be maintained by processes occurring within the arc itself. This can be most easily demonstrated for the simple thermionic arc, in which a carbon or tungsten cathode is able to supply the required electrons as a result of heating to a temperature at which adequate thermionic emission can take place. In such an arc electrons are emitted from the cathode and become accelerated under the applied field to gain energy, part of which is then lost by collision with the gas molecules so that the gas is raised to a high temperature at which it becomes thermally ionized. The positive ions so formed travel through the arc plasma in the opposite direction to that of the electrons and eventually lose a large proportion of their energy in collision with the cathode, which is thereby maintained at the temperature necessary for the emission of the required number of electrons. There are two characteristic curves which can be determined to provide information about the arc. Firstly, there is the arc-voltage/current relationship,




1—*Shape of arc-current/voltage characteristic*




2—*Variation of potential along length of arc*

which give the general external behaviour of the arc and is very important in the design of power-supply equipment for the maintenance of stable arcs. A typical example is shown in Fig. 1. The arc behaves in a completely non-ohmic manner, for with increasing current the voltage first decreases and then remains constant, only increasing slightly in the very high current range. The reason for the initial decrease in the arc voltage is twofold; firstly the conducting area of the arc column becomes larger; secondly its temperature, and hence its electrical conductivity, increases so that the required current is able to flow with less potential drop. However, the arc-voltage/current characteristic does not provide very satisfactory evidence for the internal structure of the arc; for this the change in arc potential is determined along the length of the arc (Fig. 2). There are three regions of differing potential gradient along the length of the arc. Most of the arc consists of gas at high temperature, known as the arc column or arc plasma, in which the current is carried by electrons and ions provided by thermal ionization of the gas. In the immediate vicinity of the electrodes the gas can no longer exist at a high temperature because of the cooling effect of the electrodes; the maintenance of the current requires a high potential drop so that the cathode and anode drop regions are formed.

The electrons from the column flow into the anode drop region, but as they approach the anode the temperature decreases and therefore the density of positive ions, produced by thermal ionization, decreases also, resulting in a negative space charge which is responsible for the anode potential drop. Under the influence of this potential drop the electrons are accelerated, thereby gaining kinetic energy which is then lost by collision with the anode. It is this energy, supplied by the electron stream entering the anode over a very small area, which gives the characteristic intense localized heat source of the arc that makes it so suitable for welding.

Conditions are more complicated at the cathode, for there is the possibility of several processes operating simultaneously, depending on the type of arc. A simplified model, pertaining to a thermionic arc, would be that ions travelling towards the cathode are accelerated in the cathode drop, thus acquiring kinetic energy, until they collide with the cathode surface where they become neutralized and give up their energy of recombination; they may also expend the whole or part of their kinetic energy, depending on whether they are absorbed by the cathode or reflected from it. Part of the energy thus acquired by the cathode is then used to supply energy equivalent to the work function of the emitted electrons, and the remainder compensates for conduction and radiation losses.

It is thus clear that the three regions into which the arc is divided have different functions and must therefore be considered separately. The arc column will be considered first, and the anode and cathode drop regions connecting the column to the electrodes will be discussed in later sections of the paper.

## The Arc Column

In this section it is proposed to discuss the arc column in three respects. Firstly, the state of the gas in the high-temperature zones of the arc atmosphere will be considered, so as to decide the laws of gas behaviour that can be applied. Secondly, the work of arc physicists on the arc with heat losses by radial conduction only will be described, since this shows the origin of the substructure of the arc, which is at least in part responsible for several arc welding phenomena. Thirdly, the conditions of gas flow and of heat transfer in the column of a welding arc will be discussed, so as to provide a background for the later consideration of the problems of heat and mass transfer in welding.

### State of the Arc Column and the Saha Equation

To be able to support the current between the electrodes, the arc column must be able to provide and maintain a supply of charge carriers, and these are the ions and electrons which are formed when a gas is heated to a sufficiently high temperature that the atoms become ionized. Under the applied field the ions travel to the cathode and electrons to the anode so that the current is bipolar in nature. However, as shown in Fig. 2 the potential gradient is uniform along the length of the column, which means that the positive and negative charge densities must be equal; and since the current is determined by the rate of charge movement the contribution of the ion and electron currents must be of the same order as their mobilities, *i.e.*, the ion current is less than 1% of the total current. In practice therefore it is generally possible to neglect the ion current and to make the approximation that the whole of the current is provided by the flow of electrons.

The maintenance of the current thus depends on the electron density and the size of the conducting zone, and these in turn require a region of high temperature. A high-temperature column of gas can be maintained only if sufficient energy is generated to compensate for that lost by conduction and other heat transfer processes, which are determined by the temperature and size of the conducting zone. Arcs exist with core temperatures between 5,000° and 50,000°K, and with degrees of ionization between 1% and greater than 100%, where by the latter is meant that double and even triple ionizations are not uncommon. In the main body of the welding arc column the current is generally maintained by the ionization of gas atoms, but adjacent to heavily vaporizing electrodes metal atoms can make an important contribution.

The arc column receives its energy from the electrons, which are accelerated by the applied field and then collide with the neutral gas atoms and raise its temperature. The energy or 'temperature' of the electrons must therefore always be greater than that of the remainder of the column, but in an arc at atmospheric pressure the path length of an electron before it undergoes a collision is very short, so that the electrons are never able to acquire a significantly greater energy. To consider a specific example, Busz-Peuckert and Finkelnburg[4] have found the temperature in front of the cathode of the argon arc to be 30,000°C., and at this temperature they find the collision frequency to be $4\times10^{11}$/sec, the electron mean free path length $3\times10^{-4}$ cm, and the mean temperature of the electrons to be 2% higher than that of the mean column temperature. The arc column can therefore be

considered to be in thermal equilibrium, so that the state of the gas can be calculated from standard free-energy changes employing conventional thermodynamic principles. In particular, it is possible to determine the degree of dissociation of polyatomic gases (for relevant data see appendix to Edels paper, ref. 26). It will be seen later (Table I), that almost always the column temperature of welding arcs is considerably higher than that required for complete dissociation. However, much less is known of the critical temperature region immediately adjacent to the electrodes. From the standpoint of arc physics where it is necessary to be able to relate the current intensity and temperature distributions across the arc column, the concept of thermal equilibrium allows the ionization density $N_i$ to be calculated thermodynamically from the ionization potential $V_i$ of the gas in the arc atmosphere, resulting in the Saha equation:

$$\log_{10}(N_i^2/N_0) = -5040\,(V_i/T) + 1\tfrac{1}{2}\log_{10}(T + 15{\cdot}385) \quad \ldots \quad (1)$$

where $T$ is the absolute temperature and $N_0$ is the density of atoms. For a discussion of the derivation of the Saha equation and examples of its application see Edels.[26] Curves showing the ionization density as a function of temperature for singly and multiply ionized gases can be found in Finkelnburg and Maeckers' article.[8]

A further important aspect of the state of the column is that, because of the high temperature and correspondingly low density, the particles within the column occupy a negligible proportion of the total volume and therefore do not interact, so that the ideal gas laws can be applied. The properties of the gas can therefore be calculated from established formulae of the kinetic theory of gases, provided that the collision cross sections of the various ions and atoms in the column are known. One of the aims of the arc physicist has therefore been to determine the composition of the column and the corresponding collision cross sections, so as to calculate the properties of the gas at arc temperatures.[8, 10–12]

#### Energy Balance for the Cylindrical Arc

It has been pointed out earlier in this review that the temperature distribution and the amount of gas which flows through the arc and becomes heated must in some manner determine the heat and mass transfer from the arc column to the weld metal, and that these factors are in turn related to the amount of electrical energy which is converted into heat in the column. An energy balance for the arc column exists, since the amount of energy that is dissipated must be equal to the heat losses from the column if a zone of sufficiently high temperature is to be maintained to carry the required current. The energy dissipated is $EI$ watts per unit length, where $E$ is the voltage gradient along the column. The problem now is to formulate the way in which this energy is transferred to the surroundings by the various heat transfer processes. For the welding arc it is necessary to derive an equation that takes account of the energy radiated, convected, and conducted to the surrounding cold gas and the electrodes. It has been shown by several workers that the energy transmitted by radiation from the column is at most only a few per cent of the total energy converted into heat in the column, and thus to a first approximation it can be ignored. But despite this simplification the formulation of the heat transfer equation presents a very difficult problem which has not yet been solved. To the arc physicist the short, free burning, welding arc has no particular interest, however, and effort has therefore been devoted to the solution of the case in which the arc is long, so that the effect of the electrodes can be ignored, and the energy is transported from the column by radial conduction only. The experimental arc corresponding to these conditions is obtained by operating it in a tube, uniformly cooled along its length and with a radius which is chosen to eliminate macroscopic convective gas flows. This reduces the energy balance equation to one of thermal conduction with cylindrical symmetry, and this can be readily formulated. Since the solution of this equation leads to interesting features concerning the internal structure of the arc column, which are at least part of the explanation of some of the phenomena observed in welding, a broad outline of the theory and its implications will be presented.

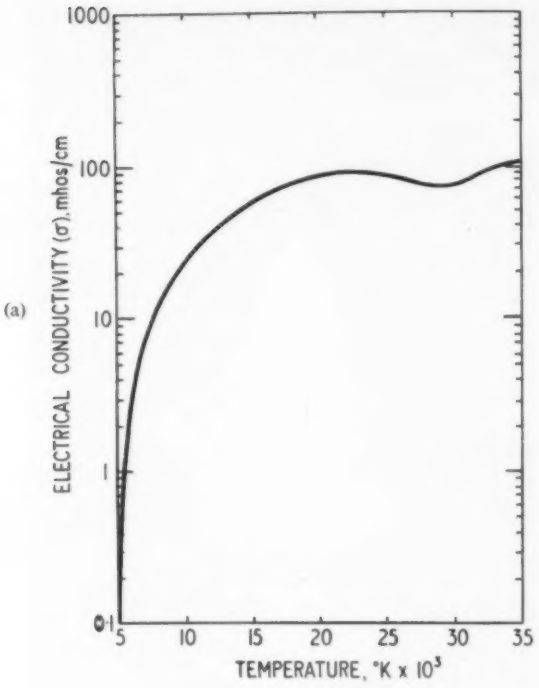
The energy balance equation for the cylindrical arc, which is known as the Elenbaas-Heller equation, is formulated by considering the heat flow across a cylindrical annulus of unit length, and thickness $dr$, at a distance $r$ from the axis of the cylinder. Applying the law of conduction, the heat generated in the cylindrical annulus brings about a change in the temperature gradient given by:

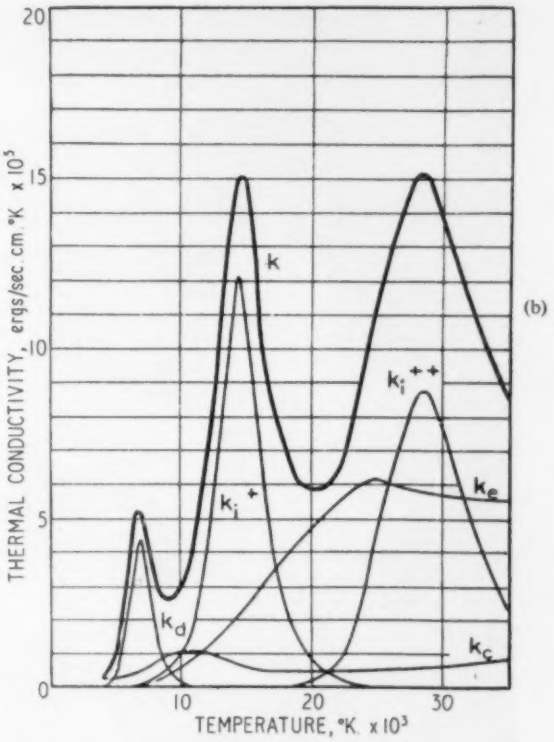
$$2\pi r \,.\, EI_r \,.\, dr = -2\pi \frac{d}{dr}\left(rk \cdot \frac{dT}{dr}\right) . dr \quad \ldots\ldots\ldots \quad (2)$$

where $k$ is the thermal conductivity of the gas and $I_r$ is the mean current density in the annulus. Simplifying, and putting the current in terms of the electrical conductivity $\sigma$ the Elenbaas-Heller equation becomes:

$$\sigma_r E^2 = \frac{-1}{r}\frac{d}{dr}\left(rk \cdot \frac{dT}{dr}\right) \quad \ldots\ldots\ldots\ldots \quad (3)$$

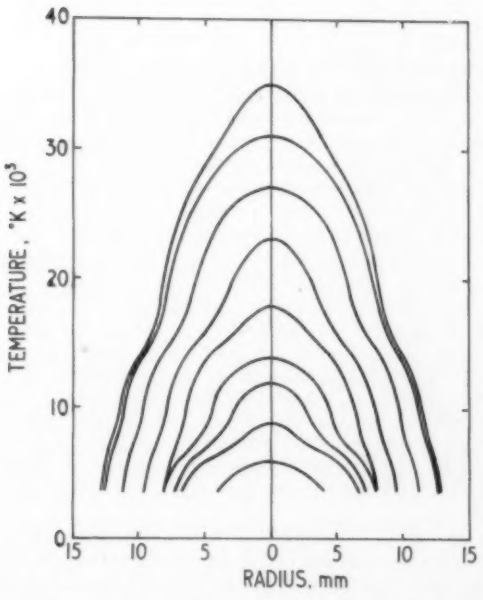
To solve this equation it is necessary to express the electrical and thermal conductivities as a function of temperature. The Saha equation is used to determine the composition of the arc atmosphere as a function of temperature. Then using the measured collision cross sections of the various constituents, the electrical and thermal conductivities are calculated from the kinetic theory of gases. Since both the electrical and thermal conductivities vary markedly with temperature the Elenbaas-Heller equation has then to be solved by long and tedious graphical or numerical methods (for a more rapid, approximate, but nevertheless 'reasonably accurate method see Goldenberg[13]). King[14, 15] has carried this calculation through for the nitrogen arc, not for the cylindrical arc burning in a cooled tube, but for the case where the heat is transported only by radial conduction and with the temperature zero at infinity, which means that as more heat is converted in the column the arc widens out. As will be shown later this case lies somewhere between the idealized but realizable case of the arc burning in a tube and the more usual circumstance of the free burning arc. King's curves for the electrical and thermal conductivity of nitrogen are given in Fig. 3, where (in Fig. 3*b*) the thermal conductivity curve has a series of peaks. The first of these relates to the dissociation of the



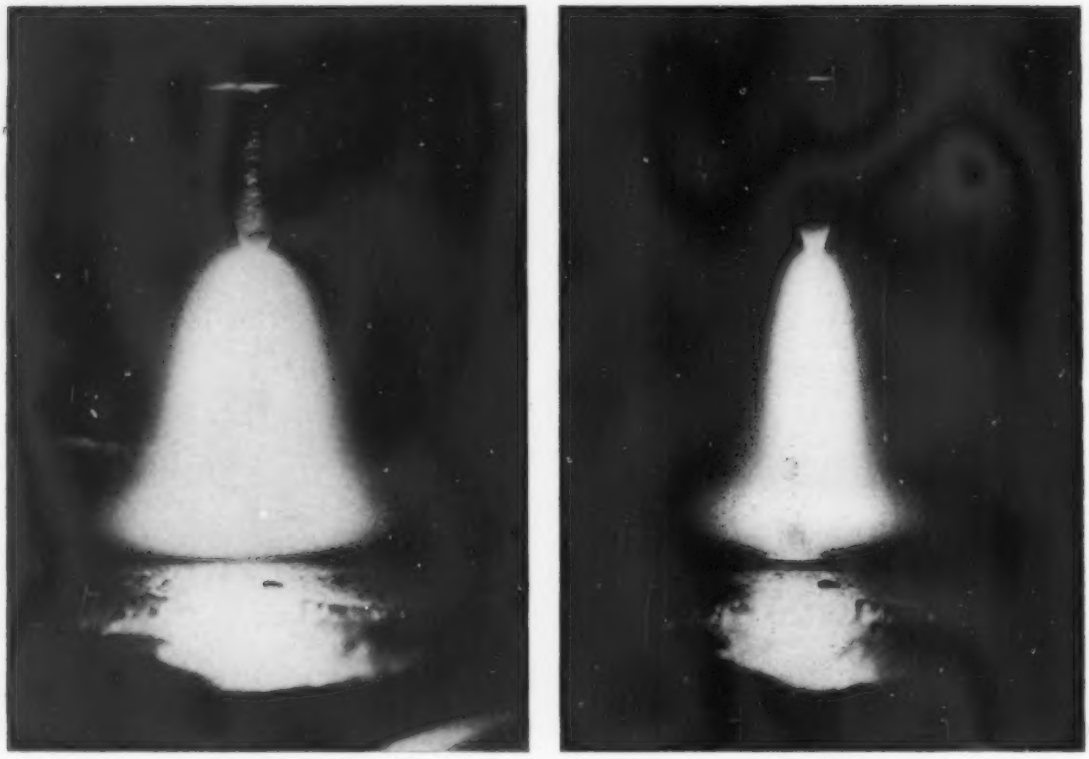

3—*Variation with temperature of:* (a) *electrical conductivity of nitrogen;* (b) *thermal conductivity of nitrogen* (*King*[14, 15]) (*Courtesy Pergammon Press*)

$k_c$ The classical conductivity due to the microscopic motions of the atoms and ions
$k_e$ The classical conductivity due to the microscopic motions of the electrons
$k_d$ Conductivity due to the diffusion of molecules and associated atoms
$k_i{}^+$ Conductivity due to the diffusion of electrons and singly ionized atoms
$k_i{}^{++}$ Conductivity due to the diffusion of electrons and doubly ionized atoms




4—*Radial temperature distribution for several axial temperatures in nitrogen arcs with conduction cooling* (*King*[14, 15]) (*Courtesy Pergammon Press*)

nitrogen molecules into atoms which, on diffusing down a temperature gradient, carry with them their energy of recombination and thus increase the rate of energy transport. Similar increases in the rate of energy transport, and hence in the thermal conductivity, are obtained when the gas becomes ionized. The peaks in the thermal conductivity curve result in a substructure in the arc column because where the thermal conductivity increases with temperature the radial temperature gradient is reduced; conversely a decrease in the thermal conductivity increases the temperature gradient. At lower temperatures the value of the thermal conductivity is much reduced, so that there is a very rapid decrease in temperature, giving a well defined boundary to the arc. Thus, when the current is sufficiently high to necessitate a core temperature in excess of that at which the dissociation peak occurs, the arc develops an inner core, as can be seen from King's temperature profile reproduced in Fig. 4 and the photographs in Fig. 5 comparing tungsten welding arcs in argon and nitrogen. Argon being monatomic cannot develop a dissociation core. The current at which the dissociation core develops



(a) (b)

*5—Photographs at same time exposure of 85-amp arcs in argon and nitrogen, demonstrating formation of inner core in diatomic gas*

depends on the dissociation potential and has been calculated by King for oxygen, nitrogen, hydrogen, and carbon dioxide and the results are shown in Table I. These figures can only be taken as a guide

**Table I**

**Dissociation characteristics and transition currents for different gases** (King[14,15])

| *Gas* | $CO_2$ | $O_2$ | $H_2$ | $N_2$ |
|---|---|---|---|---|
| Dissociation potential | 4·3 | 5·084 | 4·477 | 9·762 |
| 90% dissociation temperature, °K | 3800 | 5110 | 4575 | 8300 |
| Critical current, amp | 0·1 | 0·5 | 1·0 | 50 |

since King has shown them to increase if the column potential gradient decreases (owing to a lower rate of cooling of the column) and also if metal vapour is introduced into the column. Nevertheless, it can be seen that in all cases (except perhaps occasionally with nitrogen) the core would be expected to be present in welding arcs in dissociable gases. At higher currents, and correspondingly higher temperatures, further cores will develop corresponding to the ionization peaks, and these will be present also in the monatomic gases, argon and helium.

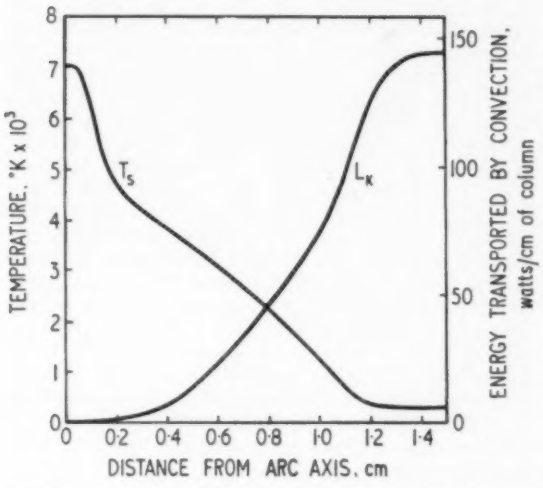
**Energy Balance for the Welding Arc**

The foregoing considerations, based on cylindrical arcs with conduction cooling, provide an understanding of some of the features found in the welding arc. The energy balance for the welding arc cannot be described solely in terms of conduction cooling because other heat transfer processes must also be considered. In addition, the welding arc is generally only a few millimetres in length so that the assumption of cylindrical symmetry would not be expected to apply.

A mathematical analysis of an arc of finite length has been made by Schmitz[16] for the case where the energy is dissipated by conduction only. He considered the column to be an isolated entity but of finite length, *i.e.*, no attempt was made to take account of any special cooling effects which the electrodes might have. Schmitz found that under these conditions the current lines and isotherms became ellipses with the focal points at the end points of the arc.

The heat transfer process that would appear to be of most likely importance in the welding arc is convection, since the arc is free burning and thus allows the heated gas to rise naturally unless there is a superimposed velocity, *e.g.*, that of the protective gas shield in argon-arc welding. The importance of convection in

the free-burning arc was demonstrated by Steenbeck who eliminated it by operating the arc in a freely falling box and found that, for a 4-amp arc in air, the arc voltage decreased by a factor of 2–3, while the current density decreased from two to five times. The only known detailed investigation of the part played in the heat transfer from the column is that of Hagenah[17] who introduced small particles of carbon into a 10-amp carbon arc and followed their path photographically; he was hence able to determine gas flow velocities of the order 50–200 cm/sec. Near the centre of the arc the gas flow was found to be parallel to the arc axis and thus parallel to the isotherms, so that no heat was transferred by convection. In the outer regions of the arc the isotherms were found to be inclined to the gas flow, and convection played an increasingly important part until at a radius of 1·3 cm it was entirely responsible for the heat transfer. The temperature distribution and the proportion of heat transferred by convection are shown in Fig. 6.




6—*Temperature distribution in 10-amp carbon arc* ($T_s$), *and amount of energy transported by convection* ($L_K$), *as a function of distance from arc axis* (*Hagenah*[17]) (*Courtesy Springer-Verlag*)

To determine an energy balance for a 'free burning' arc it is therefore necessary to take account of the part played by convection. An attempt to do this was made by Suits and Poritsky[18] who applied the results of the well established experimental and theoretical analysis developed for heat loss from a hot solid cylinder. But, as they pointed out, the convection velocities are very different, for they are zero at the surface of the solid cylinder and increase over a boundary layer adjacent to the cylinder, whereas in the arc they are probably a maximum in the inner regions of the column and decrease outwards. However, by assuming that heat loss by radiation could be ignored and that the variation of the column temperature with current could be neglected, they were able to show that current-density/voltage-gradiant relationships could be derived for the arc column which were not incompatible with those observed experimentally. The available experimental data were however insufficient to provide an adequate correlation.

In high-current arcs another type of gas flow, arising from electromagnetic forces, has been demonstrated and is known as plasma streaming or the plasma jet action. Since it would appear that this is of considerable importance in all three aspects of arc-metal interaction, *i.e.*, heat, mass, and metal transfer, with which this paper is concerned, it will be considered in some detail.

#### Plasma Jet Action

The fact that high-velocity gas flows can occur in arcs, and that there are reaction forces on the electrodes of the order of 1 gm, has been known for many years, but it was Maecker who, in 1955,[2] showed how these velocities originate and put forward a quantitative theory of plasma streaming. To illustrate the origin of the plasma jet, consider an arc consisting of a homogeneous cylindrical canal of current intensity $I$ and radius $r_a$. This will have associated with it a self-induced magnetic field, and the current and field will interact to produce a force on the charge carriers directed inwards towards the arc axis. Under the influence of this force the electrons will move towards the arc axis, but in travelling in this direction the electrons collide with the neutral atoms with a collision frequency of the order of $10^{11}$/sec, and thus carry the neutral atoms with them. A local region of high pressure is thus created in opposition to the electromagnetic force. The increase in pressure is related to the current density $j$ and therefore is a maximum at the arc axis. Maecker finds that the pressure expressed as a function of the radius is:

$$P(r) = \frac{Ij}{c^2} \cdot \left\{1 - \frac{r^2}{r_a^2}\right\} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

so that the maximum pressure is given by:

$$P_{max} = Ij/c^2 \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

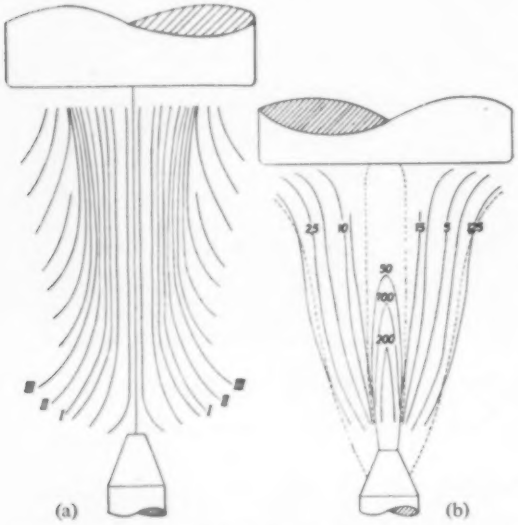
If the arc were cylindrical in form throughout its entire length, this pressure gradient would exist at every point along the column, and since the increase in pressure is small, *i.e.*, of the order of a few mm of mercury column, it would have no effect upon the arc. However, when the cross sectional area of the arc varies the increase in pressure must change, giving rise to a pressure gradient along the length of the column. In particular, where the arc is severely constricted, either naturally as in the case of a cathode spot, or artificially by, for example, forcing the arc to burn through a small hole in a water cooled copper disc, a marked region of high pressure can occur, and the arc plasma flows from the high pressure region to adjacent low pressure regions. To maintain continuity of flow, gas is sucked into the constriction from the surrounding atmosphere so that the constriction acts as a pump. A plasma flow occurs with the carbon arc burning in air, where the constriction is provided by the naturally occurring cathode spot, which has been investigated in detail at 200 amp. For this case Maecker gives the diameter of the cathode spot as 0·24 cm, which corresponds to an increase in pressure at the axis of 7 mm mercury column, while the fully developed core of the arc has a radius of 0·4 cm with a corresponding increase in pressure of 0·6 mm mercury

column. From this pressure gradient the maximum theoretical velocity, which is determined from the equation:

$$\frac{Ij}{c^2} = \frac{\bar{\rho} v^2_{max}}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

is given as about $3{\cdot}5 \times 10^4$ cm/sec, where $\rho$ is the mean plasma density.

The velocity and flow field for the 200-amp carbon arc have been determined experimentally by Wienecke,[19] who introduced and photographed small particles to measure the velocity in the outer regions of the plasma jet, whilst the velocity in the core was determined by super-high-speed photography of the passage of an artificially induced electrical interruption as it transversed the arc. His results are shown in Fig. 7 from which it can be seen that the velocity varies from $2 \times 10^4$ cm/sec for a small central core to




7—(a) *Pattern of gas flow induced by plasma jet in 200-amp carbon arc;* (b) *curves of equal velocity (m/sec)* (*Weinecke*[19]) (*Courtesy Springer-Verlag*)

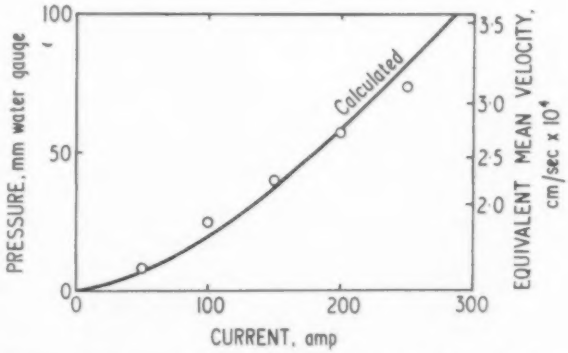
about $10^3$–$10^2$ cm/sec near the anode. Where plasma streaming is operative, cold gas is sucked into the arc column from around the cathode and, on entering the column, is heated to the column temperature. This requires the conversion of energy, resulting in an increased voltage drop, of the order of 1 volt, in this region (Muller and Finkelnburg[20]). Since the heated gas passes along the column, the mode of heat transfer depends on the relation of the gas flow to the isotherms; if both gas flow and isotherms are parallel to the axis no heat is transferred by convection in this region, and energy will pass outwards by conduction and in the outer zones be used to heat the surrounding cold gas that is dragged along by the plasma jet.

Since the existence of plasma jets requires a constriction in the arc, they would be expected to occur with tungsten-arc welding, where the constriction is provided by the naturally occurring cathode spot, and in general when welding with a consumable electrode since the current is constrained by the diameter of the wire. It would also be expected that a small electrode diameter would result in a more intense jet, so that this should be quite pronounced in the inert-gas shielded metal-arc welding process, which utilizes small diameter wire electrodes. The plasma jet becomes more intense as dissociation and ionization cores develop in the arc adjacent to the electrodes, since these cause a marked increase in the current density. It is also possible to make jets occur from both electrodes, in which case the jets interact to give a complex flow pattern.

Whilst it can be shown in general terms that high-velocity plasma jets probably exist in welding arcs, no evidence is available to show the welding conditions under which they occur or their extent and velocity. Since, as will be shown later, these jets are of fundamental importance in welding it is necessary to consider how they can be investigated. In the first place the existence of a jet bears a rough relation to the appearance of the arc. If the arc broadens out appreciably from areas of constriction then there is a change in the current density along the length of the arc and this is indicative of the presence of a jet. The limitation to the quantitative use of this observation is that the observed arc does not necessarily give a measure of the current-carrying region, since light intensity is related to the excitation of the gas in the arc atmosphere, whereas the current is determined by the ionization. However, if it is possible to relate the observed temperature contours to the current flow, then Maecker's procedure can be used to calculate the pressure increase and the corresponding maximum velocity. Where a non-consumable electrode is used it is possible to make an experimental determination of the pressure increase immediately in front of the electrode by boring a small hole through it and connecting it to a manometer. Maecker measured this pressure by drilling a 1 mm hole in a carbon cathode, and obtained the increase in pressure as a function of the current shown in Fig. 8. The present authors have added a scale in which pressures have been converted to mean velocities by the formula:

$$\Delta p = \tfrac{1}{2}\rho v^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

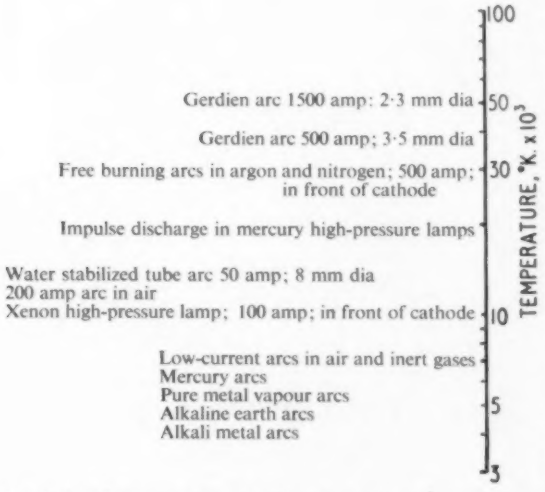
Some degree of approximation is involved but nevertheless it demonstrates the magnitude of the velocities




8—*Pressure increase in front of carbon cathode as a function of current, measured by connecting manometer to 1 mm hole drilled through cathode* (*Maecker*[2]) (*Courtesy Springer-Verlag*)

to be expected. A method of determining the total back pressure exerted on a non-consumable electrode was developed by Rohloff[21] who floated the electrode on mercury so that the depth of immersion determined the force. A method for the more difficult determination of the force on a consumable electrode was devised by Doan and Lorentz[22] who balanced the force against the tension on a calibrated spring. Whilst these determinations of reaction pressure demonstrate the existence of plasma jets they do not lead readily to determinations of their extent or velocity. The direct measurement of jet velocity, by introducing particles into the arc stream and determining the length of traces on photographic film, requires exposures that are not readily attainable when the particle velocities are of the order of $10^4$–$10^5$ cm/sec, and is in any case complicated by the presence of metal globules in the important case of consumable electrode welding.

The full significance of plasma jets in welding arcs has yet to be determined, but the other papers in this series show that they are responsible for metal transfer and for the transport of gas through the arc to the weld metal surface, and thus play an important part in mass and heat transfer. They are also the probable cause of cratering of the weld pool, whilst the intense plasma jets associated with dissociation cores are at least partly responsible for the action of deep-penetration electrodes, and the ionization core for the deep-penetration toe in inert-gas shielded-arc welding. Plasma jets must also be of considerable importance in determining the effectiveness of the protective gas shield in tungsten-arc welding. The gas flows through the nozzle at about $10^2$ cm/sec, and in the centre of this shroud the arc is sucking in gas to form a plasma jet with a velocity of about $10^4$ cm/sec. If the jet action becomes very strong the gas shield will not be able to provide adequate protection and this may explain the difficulty in maintaining efficient shielding at high currents,[23, 24] when the plasma jet action would be expected to be intense.


Gerdien arc 1500 amp: 2·3 mm dia
Gerdien arc 500 amp; 3·5 mm dia
Free burning arcs in argon and nitrogen; 500 amp; in front of cathode
Impulse discharge in mercury high-pressure lamps
Water stabilized tube arc 50 amp; 8 mm dia
200 amp arc in air
Xenon high-pressure lamp; 100 amp; in front of cathode
Low-current arcs in air and inert gases
Mercury arcs
Pure metal vapour arcs
Alkaline earth arcs
Alkali metal arcs
100
50
30
10
5
3
TEMPERATURE, °K. x 10³

9—*Scale of temperatures occurring in various types of arc (Finkelnburg and Maecker[8]) (Courtesy Springer-Verlag)*

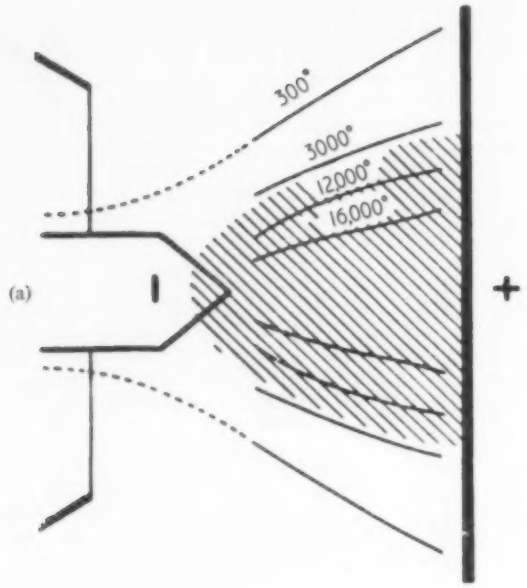
**Temperature of the Arc Column**

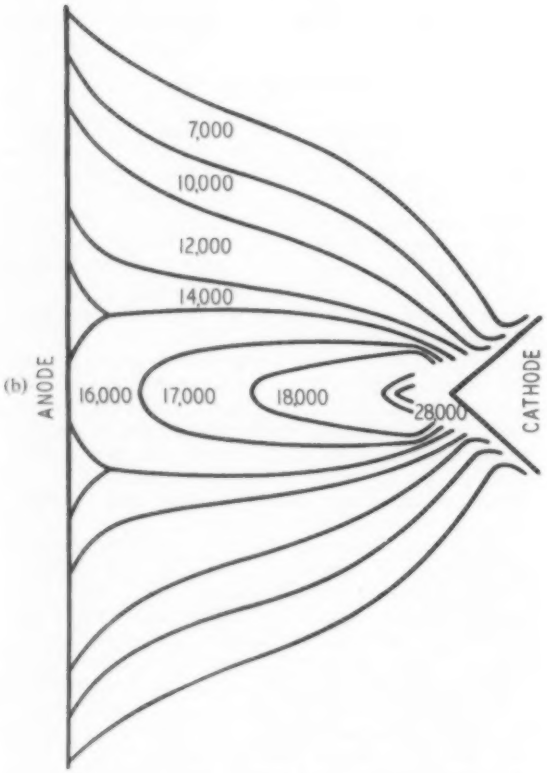
The temperature of the gas in the arc column is an important parameter in dealing with arc/metal interactions. In general terms the Elenbaas-Heller equation shows that a high gas thermal conductivity, a high rate of cooling, and a high ionization potential of the arc atmosphere all lead to high column temperatures. Finkelnburg and Maecker have prepared a diagram which shows the relative temperature of various arc types (Fig. 9). It is probable that the fundamentals of arc/metal interactions will be initially established by researches on the inert-gas shielded processes, since these offer the most amenable systems for investigation, so that a knowledge of the temperature distribution in this case is particularly important. For this reason the determinations of Busz-Peuckert and Finkelnburg[4] of the temperature distribution in an argon arc operating between a tungsten cathode and a water cooled copper anode are of special significance. These workers were able to determine the position of the 16,000°C. isotherm and of lower temperature isotherms for the 200-amp arc, as shown in Fig. 10*a*, whilst the temperature distribution in the 500-amp arc was given later[25] and is reproduced in Fig. 10*b*. They concluded that the axis temperature at a few millimetres in front of the cathode was about 25,000°C. at 200 amp and 30,000°C. at 500 amp, and that the axis temperature in the nitrogen arc was of a similar order. The methods that can be used for the determination of temperatures in arcs have been reviewed in references 8, 11 and 26.

## The Constricted Arc

It will be appreciated from the foregoing discussion of the mechanism of current transfer in the arc column that it is necessary to produce and maintain the required conducting cross section of charge carriers. For a given current, if the conducting cross section is large, the charge density and hence the gas temperature is relatively low, and conversely, if the conducting cross section is small, the charge density and the temperature must be high. This leads to the interesting phenomenon that an increase in the cooling of the arc column, thereby restricting its area, increases the core temperature so as to maintain the current; this is reflected in a higher arc voltage. This principle has been applied to produce high-velocity gas jets having temperatures up to 50,000°C., which are now finding considerable industrial application, particularly for welding, cutting, and metal spraying, and therefore merit detailed consideration here.

The initial realization that high gas temperatures are produced by constricting an arc is attributable to Gerdien and Lotz in 1923.[3] These workers were concerned with obtaining a very bright light source and used the experimental arrangement shown in Fig. 11, in which water flows tangentially into a hole in a copper diaphragm and thus cools the inner surface, and is ejected as spray from the ends of the diaphragm. By burning the arc through this diaphragm Gerdien and Lotz were able to severely constrict the arc and thus considerably increase its brightness. They showed that this was achieved only with an increase in expenditure of energy, as shown by their voltage/current curve (Fig. 12). This shows, firstly, a higher voltage

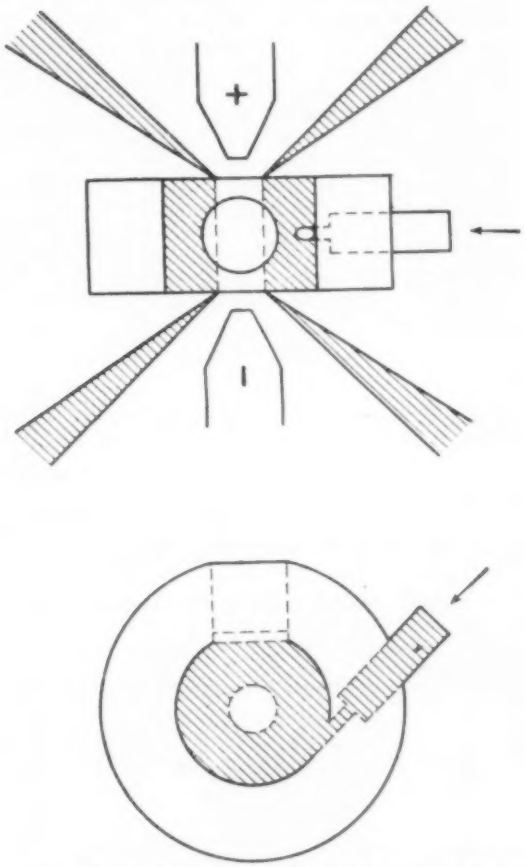


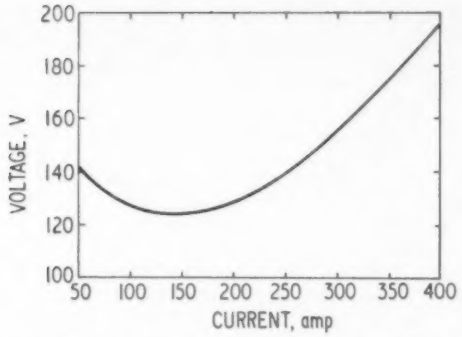

10—*Temperature distribution in*: (a) *1 cm, 200-amp argon arc operated between tungsten cathode and water-cooled copper anode (Busz-Peuckert and Finkelnburg[4]) (Courtesy Springer-Verlag); (b) in 500-amp argon arc (Finkelnburg[25])*

than would be expected for a free burning arc and, secondly, a rising characteristic as more current is required to flow through the constriction. Gerdien and Lotz realized that the expenditure of such large quantities of energy (24 kW/cm at 600 amp) in a restricted volume must lead to very high temperatures, but were unable to measure them.

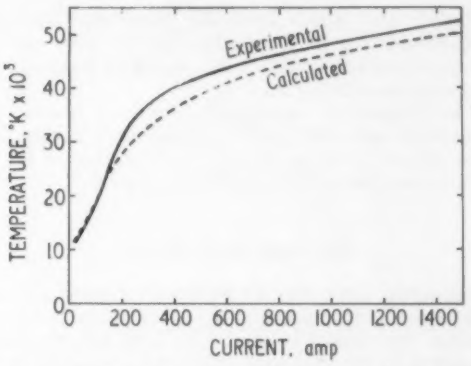
Larenz showed in 1951[27] that the radial temperature distribution in a constricted arc could be determined from the variation in intensity across the arc of selected spectra lines, and made some measurements on the Gerdien-type arc. The most comprehensive survey of constricted arc temperatures to date was, however, made by Burhorn, Maecker, and Peters in 1951[28] who, to obtain the stable conditions necessary for accurate temperature measurements, developed the Gerdien-Lotz principle to produce a long arc in a 2·3 mm dia. water-cooled tube which has since become known as the water-pipe arc. These workers were able to determine maximum temperatures and radial temperature distributions with reasonable accuracy for arc currents varying from 112 to 1500 amp, obtaining the results shown in Figs. 13 and 14. The maximum temperature at first increases rapidly with current, attaining 40,000°C. at 400 amp, but a further



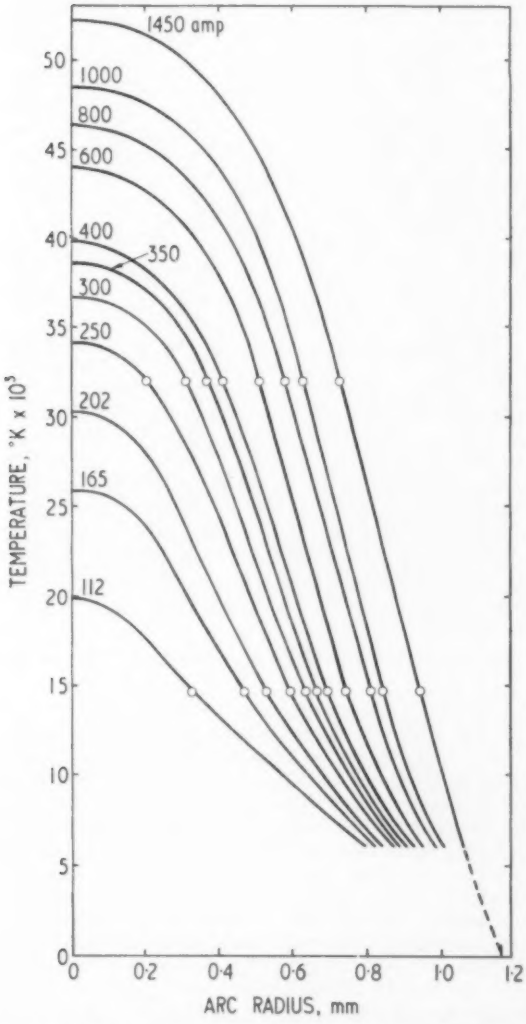

11—*Apparatus used by Gerdien and Lotz[3] to constrict an arc; water flow shaded*




12—*Rising arc characteristic obtained by Gerdien and Lotz[3] with their constricted arc*




14—*Variation of axial temperature with current for water-pipe arc (Burhorn, Maecker and Peters[28]) (Courtesy Springer-Verlag)*




13—*Radial temperature distribution in water-pipe arc for currents from 100 to 1450 amp (Burhorn, Maecker and Peters[28]) (Courtesy Springer-Verlag)*

increase in the current to 1200 amp is then necessary to raise the maximum temperature to 50,000°C.

From the welding and cutting standpoint a more interesting technique for constricting the arc is to burn it in a tube and to effect the cooling and constricting by means of a gas flowing axially along the tube. In this way it is possible to produce a high-temperature, high-velocity gas jet. The commercial potentiality of the constricted arc for the cutting and welding of metals was first realised and patented by Gage[29] in 1955, in a device that is essentially an inert-gas-shielded non-comsumable-electrode welding torch, with the normal ceramic shroud replaced by a water-cooled copper nozzle containing a small hole through which the arc burns and the gas is forced. Since that time there has been considerable interest in the commercial potentialities of the constricted arc and many patents have been filed, in particular one in which a filler wire is fed into the plasma jet to provide a stream of molten metal for welding, metal spraying, and surface overlaying.[30]

In the various devices described so far the arc column has been constricted by cooled walls. Another method that is finding some application is to dispense with constricting walls, and to enclose the arc in a chamber and to use an anode with a small hole in its centre. Any fluid which is then forced through the anode hole cools and constricts the arc and a high-temperature plasma jet issues from the anode. This principle was initially developed by Wiess[31] who operated the arc in a chamber partially filled with water, which was vaporized by the arc heat. Peters[32] used the same technique to obtain a supersonic plasma jet of Mach 1·6 and temperature 8,000°C. by replacing the hole in the anode by a Laval nozzle. It is not known whether any attempts have been made to incorporate the Laval nozzle for cutting or other applications, although its use for the oxygen stream was found to increase efficiency in the conventional oxygen cutting of ferrous metals.[33,34]

Plasma jet projectors of the hole-in-anode type have several potential industrial applications other than for welding and cutting, so that considerable effort is being directed to their technological development.[35,36] Commercial equipments have recently become available which are claimed to cut the most refractory

materials and which have the advantage over the wall-cooled type of constrictor in that they can be operated independently of the electrical conductivity of the material being cut.

The subject of constricted arcs and plasma jet projectors and their technological applications has been treated more comprehensively in another paper in this series presented verbally by Moss.*

### The Anode Drop Region

The anode drop region forms the electrical connection between the anode and the arc column. In the arc column the current is carried by ions and electrons produced by thermal ionization, but as the anode is approached the temperature changes from that of the column to that of the anode, which is considerably lower, so that insufficient ions are formed by equilibrium thermal ionization to maintain the continuity of the ion flow. Hence the concentration of positive ions decreases, resulting in the negative space charge which is responsible for the anode potential drop. Positive ions must be formed in the anode drop region and flow into the column, so that an understanding of the anode drop requires a knowledge of the source of ion supply, which can be related to the anode potential drop and the energy balance at the anode. Although some progress has been made towards this end the theory is still incomplete, and the following is an assessment of the relationship between the present state of knowledge of the physics of the anode drop, as expounded by Finkelnburg and Maecker, and the function of the anode drop region in welding.

In the anode drop region three phenomena must occur. The temperature must fall from that of the column to that of the anode; a supply of ions must be produced to flow into the arc column; and the ions so produced must be accelerated, and thereby raised to the arc column temperature, by the time they reach the boundary of the anode drop region and enter the column. The mechanism of formation of the positive ions is dependent upon the anode plasma composition and temperature. If the temperature of the anode plasma is low the high-energy electrons entering it from the column undergo few collisions and are thereby able to acquire a sufficient energy to ionize or, in the case of stage ionization, excite in a single collision. This is known as field ionization and is associated with a low anode plasma temperature and a relatively high anode drop, of the order of at least the first excitation potential of the anode plasma gas. As the temperature of the anode plasma is increased, *e.g.*, by increasing the current density, the possibility of the production of an adequate supply of positive ions by thermal ionization increases. It is only necessary to produce about 1 ion for every $10^3$ electrons flowing into the anode drop region, and in the normal Maxwell energy distribution in the emanation from the column there is a small proportion of high-energy electrons. As the mechanism becomes closer to that of thermal ionization, the less is the increase in potential needed, so that the anode drop is lower.

Gas and vapour streams can have a very marked effect on the anode drop if they have a velocity of the same order as or greater than the ion drift velocity, *i.e.*, of the order of $10^2$ cm/sec. It has been shown, for example, that an anomalously high anode drop occurs with the high-current carbon arc having a rapidly vaporizing anode, because the vaporized material flows off as an anode jet with a velocity of $1 \cdot 10^2$–$7 \cdot 10^2$ cm/sec, which blows the ions away from the anode drop region so that more have to be formed and the anode drop is increased (*see* ref. 8 section 121). The electron stream is unaffected because of its high velocity. A plasma jet originating from the cathode has the reverse effect, since it prevents the flow of ions away from the anode region and also influences the temperature distribution in front of the anode by forced convection to the anode surface. Thus Müller and Finkelnburg[20] found for a carbon arc at 200 amp with a well formed cathode plasma jet, but with a large non-vaporizing anode surface, an anode drop of only $1 \pm 2$ V. The metal vapour, which is always liable to be present in welding arcs, could exert a very marked effect on the anode drop, for it would supply a source of low ionization-potential positive ions. The influence of metal ions on the anode drop of low-current arcs has been clearly demonstrated (ref. 8 section 110). Thus, for the low-current carbon arc, the addition of metal salts to the anode caused a marked decrease in the anode drop, whilst for the metal or metal oxide anodes a correlation has been found between the anode drop and the ionization potential of the anode material. With high-current arcs the relative significance of plasma streams and the composition of the anode has yet to be determined.

The energy balance at the anode is particularly important, for it determines the melting of metal to form a weld pool in straight-polarity welding, and the melting of the electrode in reverse-polarity welding. In low-current arcs it is possible to make the approximation that the electrons undergo a free fall in the anode drop, so that they arrive at the anode with the thermal energy $3kT/2$, which they had in the arc column, plus that aquired as a result of acceleration through the anode drop $V_a$, and on entering the anode give up their heat of condensation $I\phi$ (where $\phi$ is the work function of the anode material). The heat entering the anode $H_a$ is therefore

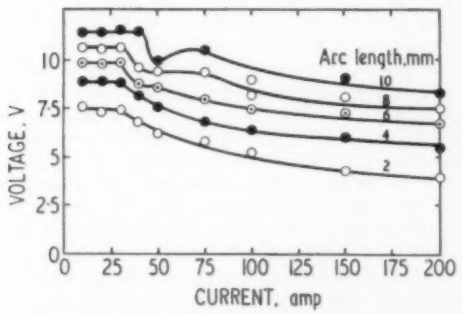
$$H_a = I\phi + IV_a + \frac{3kTI}{2e} \quad \ldots\ldots\ldots\ldots \quad (8)$$

in which $V_a$ is assumed to be constant.

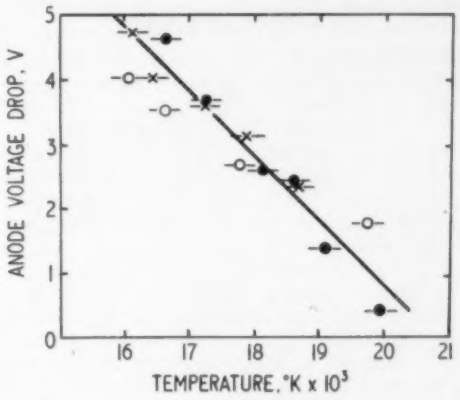
It has generally been assumed that the same conditions apply to the welding arc, but the low anode drops obtained are consistent with a thermal mechanism in which the electrons do not fall freely through the anode drop but undergo a number of collisions. However, since in broad terms the anode drop exists so as to overcome the cooling effect of the anode, equation (8) can probably be regarded as a reasonable first approximation. Experimental determinations of the anode heat input of the welding arc are generally made as a function of arc length, and show an appreciable increase in anode heating with increasing arc length. In the interpretation of these results it has generally been assumed that the same conditions pertain as in the low-current arc, *i.e.*, the anode drop is invariant with respect to arc length, and the anode

* A 'restricted' report not available for publication.

heat input obtained by extrapolation back to zero arc length gives the value of $H_a$ in equation (8), from which the anode potential drop can be estimated. It would be more satisfactory if direct determinations were made of the characteristics of the anode drop region, particularly of the anode potential drop, but this is very difficult and in fact the only known measurements of any relevance do not appear to concur with practical experience. Thus Apps and Milner[37] using a conventional argon-arc torch measured the anode heat input to specimens which were allowed to form a molten pool and correlated these results with measurements of weld bead widths. These workers found that, although the heat input to the anode increased significantly with arc length, the width of the weld bead remained constant. This is quite a critical test for it can be shown from Well's equation[38] that once a fused zone is formed, only a relatively small amount of heat is needed to increase the bead width appreciably. Thus, for a specific set of conditions examined by Apps and Milner for aluminium, the weld bead width equivalent to zero arc length was 0·47 cm, with a heat input of 192 cal/sec, whilst at 0·5 cm the heat input had increased to 224 cal/sec. This should have increased the weld bead width to 0·63 cm, whereas no measurable increase could be detected, although isotherms further away from the source of heat were appreciably widened. Apps and Milner interpreted this result as meaning that the anode drop, and therefore the localized intense concentration of heat, remained constant with arc length, but that as the arc length was increased a more diffuse source from the column was superimposed on the intense electron source which did not contribute to the width of the fused zone. This does not concur with the recent comprehensive survey of anode drops and anode heating made by Busz-Peuckert and Finkelnburg[5, 6] for a system in which an arc was operated in atmospheres of argon and nitrogen with a tungsten cathode and water-cooled copper plate as the anode. These authors measured the heat input to the anode and also made probe determinations of the anode drop. They found that the anode drop varied both with arc length and current (*see* Fig. 15) and concluded that it was related to the temperature of the plasma immediately adjacent to the anode (Fig. 16). Busz-Peuckert and Finkelnburg postulated that the anode drop was determined by plasma jets within the arc; if there was




15—*Variation of anode drop with current for several arc lengths, determined by Busz-Peuckert and Finkelnburg[5, 6] for argon arc operating between tungsten cathode and water-cooled copper anode (Courtesy Springer-Verlag)*




16—*Relationship between anode drop $V_a$ and temperature o plasma immediately in front of anode, found by Busz-Peuckert and Finkelnburg[5, 6]*

an anode jet it blew ions away from the anode plasma region which had to be replaced at the expense of a high anode potential drop, whereas if there was an over-riding cathode plasma jet it prevented the flow of positive ions from the anode plasma region, and the anode drop was correspondingly low. At low currents, *e.g.*, 20 amp, the heat input to the anode was determined by the anode drop and the heat of condensation of the electrons; at high current, *e.g.*, 200 amp, most of the heat dissipated in the arc column also appeared to be absorbed by the anode. It is possible, particularly in view of the importance assigned to anode vapour jets, that the difference between experience from the welding field and the results obtained by Busz-Peuckert and Finkelnburg is due to the presence of the molten weld pool and hence of metal vapour.

An interesting example of the relation between the anode drop, the anode heat input, and the formation of the weld bead was investigated by Ludwig.[39] He made weld runs (without filler metal), using the inert non-consumable electrode process with helium shielding, on Zircalloy produced by the inert-gas arc-melting process and by vacuum arc melting. He found that the penetration was greater with the inert-gas-melted material as a result of a greater anode heat input, and related this to the chlorine content of the metal, which was 32 p.p.m. in the inert-gas-melted material as against 6 p.p.m. in the vacuum-arc-melted metal. The explanation advanced was that chlorine emanated from the weld pool and supplied negative ions to the anode drop which increased the negative space charge and anode potential drop and hence the dissipation of energy in the anode region. This would be in keeping with the concept of a cathode plasma jet controlled anode drop, which probably occurs with a water-cooled tungsten cathode operating on a large weld plate. If, however, the chlorine escaping from the metal surface were sufficient to provide an anode vapour jet it could increase the anode drop by ion loss as described previously.

The results of experimental determinations of the anode drop and a more detailed discussion of the anode drop region in the argon arc are given in a further paper in this series (*see* p. 115).

### The Cathode Drop Region

The electrical connection between the cathode and the arc column is a region in which there is a marked potential drop (known as the cathode drop region) which is considered to be contained within two imaginary planes, one situated just inside the cathode surface and the other at the beginning of the equilibrium arc column. This region is of importance in welding because it is here that the electrons must be produced to flow into the arc plasma, and the ease of production and maintenance of this electron supply to a large extent determines the stability of the arc. The heat that is dissipated in the cathode drop region is used in part to create the supply of electrons and to melt the electrode in straight-polarity welding and to form the weld pool in reverse-polarity welding. The localized high-energy dissipation also creates a region of marked chemical activity similar to that existing at the anode. In a.c. welding the processes occurring in the cathode region have a critical significance because of the need for arc reignition every half cycle.

Whereas the knowledge of the arc column has been advanced as a result of the theoretical and experimental application of the Elenbaas-Heller equation and the discovery of the origin of plasma jets, and more detailed and accurate measurements have been made of the processes occurring at the anode, the theory of the cathode drop region, by comparison, has remained relatively static. Historically, the first cathode drop mechanism postulated was that electrons were supplied from the cathode at high temperature by thermionic emmission and accelerated in the cathode drop, thus gaining kinetic energy which was then lost by collisions with atoms or molecules in the arc column. The thermal ions so produced were accelerated towards the cathode and on impact gave up their kinetic energy of neutralization, so maintaining the cathode at the high temperature necessary for the emmission of the electrons. However, quantitative calculations made by the application of Richardson's equation showed that, although this mechanism was possible for the high-melting-point low-work-function materials, such as carbon or tungsten, it would not account for the high current densities achieved with low-melting-point electrodes. Various other mechanisms have been postulated but the processes occurring in the cathode drop region are still not very well understood. The difficulties are twofold: firstly, there is the problem of making physical measurements in very small regions at exceedingly high temperatures; secondly, as Loeb[40] has pointed out, the very high localized energy dissipation produces a state of matter which is difficult to analyse theoretically. Thus, to quote the figures of Finkelnburg and Maecker (ref. 8 section 102) for a current density of $10^6$ amp/sq.cm and with 10% of the current at the cathode carried by positive ions, there would be $6\times10^{23}$ ions striking unit area of surface per sec; but each unit area of surface contains only $10^{15}$ atoms, so that each atom is struck $10^8$ times per sec by ions with considerably greater energy than that possessed by the atoms. Energies dissipated in the cathode spot are of the order of $10^3$ kW/sq.cm, and in these circumstances the meaning of classical concepts, such as work function and vaporization, becomes obscure. Nevertheless, without an alternative approach attempts have been made to apply conventional concepts, and various theories have been evolved. Finkelnburg and Maecker have collated the postulated cathode mechanism with the experimentally observed characteristics of cathodes into three possible extreme cases, where in practice two of these mechanisms may be operating simultaneously or the mechanism may change from one type to another with a change in, for example, current intensity, or pressure. The three mechanisms are:

(i) Thermal emission, which is characterized by the lack of a well defined cathode spot and a low-current density, of the order of $10^3$ amp/sq.cm
(ii) Plasma emission, which is associated with a stationary cathode spot and marked contraction of the arc column immediately adjacent to the cathode. The current density at the cathode is several orders higher than with thermal emission, *i.e.*, $10^4$–$10^7$ amp/sq.cm.
(iii) Field emission, which again is associated with a well defined cathode spot, but which in this case is non-stationary, moving around with velocities of the order of $10^4$ cm/sec. The current density for field emission appears to be about one order of magnitude higher than with plasma emission.

Thermal emission is the process already described as the first hypothesis advanced to explain the mechanism by which the necessary electrons are produced in the cathode drop region to feed into the column. The thermally emitted electrons are accelerated under the applied field and undergo collisions with the gas molecules and atoms to produce positive ions which, owing to their very low mobility, move only slowly towards the cathode and are thereby responsible for the space charge which is the origin of the cathode potential drop. The thermal emission would appear to take place relatively uniformly over the heated surface of the cathode, and adjacent to the cathode there is a dark space of about $10^{-2}$ cm in extent showing that the plasma cannot maintain its high temperature in this region in opposition to the locally increased cooling from the presence of the cathode. This theory is relatively well known and will not be discussed further. The thermal emission mechanism occurs in welding with the non-consumable tungsten-electrode processes and in the now nearly obsolete carbon-arc process.

The second cathode drop theory, *i.e.*, plasma emission, probably relates only to low-current, high-pressure arcs with non-vaporizing cathodes, and so will not be considered at length here since such cathodes do not occur in welding. Briefly, this theory postulates that the cathode emits a flow of electrons which is only a small proportion of the total current, but that these electrons are accelerated and gain sufficient energy over only one or two mean free path lengths to be able to raise the gas to a very high temperature, at which it is sufficiently ionized to be able to provide the bulk of the current by an ion flow towards the cathode. On impact with the cathode the ions give up their energy of neutralization and rebound as high-energy neutral atoms, thus helping to maintain the high-temperature plasma region near the cathode. The difference between this mechanism and that of thermal emission is that in plasma emission the cathode potential drop occurs over only a few mean free path lengths, so that the high-temperature plasma exists to within this extremely short distance from the

cathode. This can occur only if the cooling effect exerted by the cathode is small, and this in turn is possible only if the arc is highly contracted immediately in front of the cathode, so that the area from which the energy is conducted is very small. Thus the cathode is joined to the column by a very high-temperature constricted region in which the cathode drop takes place and which is not therefore in thermal equilibrium. These highly contracted cathode regions have been observed in low-current high-pressure arcs.

The third type of cathode mechanism, field emission, has been invoked to explain the cathode drop phenomena occurring with low-melting-point electrodes. In this case well defined cathode spots are observed which move around with a velocity of the order of $10^4$ cm/sec. At any one time there may be many of these cathodes spots present and they are constantly vanishing and being reformed elsewhere. In general, vaporization of the electrode accompanies this type of arc. The current density is several powers of ten higher than with thermal emission, and at least one power of ten higher than with plasma emission, so that the comments made with regard to the energy input and the associated difficulty of defining the state of matter in the cathode region are even more relevant in this case, and the accepted concepts of work function and vaporization are inapplicable. For this reason, no satisfactory theory of the cathode mechanism has been developed for this type of arc. From Langmuir onward the predominant view has been that the current at the cathode is carried mainly by field emission electrons. On the basis of this mechanism and by using classical concepts, Wasserab[41] has calculated the space charge necessary for the field intensity and thus the ratio of ion to electron current and the energy balance at the cathode surface for a mercury arc. His values were later corrected (Finkelnburg and Maecker) and are now given as $(j^+/j^-)=1$ and cathode field intensity$=1{\cdot}3\times10^8$ V/cm, where the cathode current density is $2\times10^7$ amp/sq.cm. From the heat balance at the cathode, Wasserab arrives at a cathode spot temperature of about 2,100°K. and a mercury vapour pressure in front of the cathode of 2,000 atm, corresponding to an atom density of about 40% of the liquid. Whilst these figures are probably inaccurate because of the uncertainties concerning the state of the surface, they serve to indicate the sort of conditions that could exist.

This type of cathode mechanism is predominant in welding with consumable electrodes. It occurs also with tungsten electrodes operating below a temperature at which thermionic emission can occur, and has been shown by Orton and Needham[1] to be the cause of 'inverse rectification' in a.c. argonarc welding. As is well known with this process, unless steps are taken to overcome it, the arc will readily reignite on the half cycle in which the thermionically emitting tungsten electrode is the cathode, but not on the half cycle when the aluminium or other weld metal is the cathode so that rectification occurs. However, if reignition of the arc with aluminium as the cathode is brought about by a superimposed low-power high-potential voltage, then until the tungsten becomes sufficiently heated it is possible for the aluminium cathode half cycle to reignite readily but not the tungsten half cycle. This is because the field (or plasma) emission depends on the existence of a high-temperature plasma which forms, or disperses in about $10^{-3}$ sec, whereas the thermionic arc depends for its existence on the high-temperature, high-thermal-capacity cathode which takes a very much longer time to 'fade'.

From the standpoint of welding, the energy balance at the cathode is of particular significance. Heat is imparted to the cathode by the positive ions that impinge on the surface, and this is used to melt the cathode and to overcome losses by conduction and radiation. But a quantitative calculation would require a knowledge of the accommodation coefficient of the ions arriving at the cathode surface and of the proportion of the current carried by positive ions in this region. The work of Weizel and Thouret[42] would suggest that heat conduction from the column to the cathode surface may also play an important part. The preceding discussion of the theories of the cathode mechanism shows that none of the above factors is known to any useful degree of accuracy, so that no detailed energy balance can be constructed. In broad terms it is possible to state that the energy expended in the cathode drop region is used to provide the current carrying stream of electrons which enter the column with energy $3kTI/2e$, and to heat any gas or vapour flowing through the cathode drop while the remainder finds its way into the cathode by unspecified mechanisms.

## Conclusion

The three arc-metal interactions of mass, heat, and metal transfer have been basic problems in arc welding since the introduction of the process over sixty years ago, yet little is known of the principles and processes involved. There were two reasons for this: Firstly, the metal-arc welding system is complex and difficult to investigate experimentally; secondly, the fundamentals of arc physics necessary for the interpretation of data from welding systems had not been developed, so that early investigators did not reap their due reward. The situation has been very much improved in both respects; by the introduction of the inert-gas shielded-arc welding processes, which are much more amenable to investigation, and by the marked advances that have been made in arc physics in the past decade. In particular, the elucidation of the plasma jet and the energy balance and internal structure of the arc column should lead to a greatly improved understanding of those welding phenomena in which the arc column plays an important part. The conditions at the anode, and the factors which control the anode drop are now better understood as a result of the awareness of the role of anode and cathode jets, and the results of experimental investigations of welding systems should be easier to interpret. By contrast, knowledge of conditions at the cathode has remained relatively static, so that researches into the welding problems which depend on these would probably not be so fruitful at the present time.

## Acknowledgments

The authors wish to thank L. A. King and J. C. Needham, of the Electrical Research Association, for

help received from stimulating and informative discussions and for reading and commenting on the manuscript of the paper. Thanks are also due to the following publishers for permission to reproduce illustrations: Pergammon Press (Figs. 3 and 4); Springer-Verlag (Figs. 6–10 and 13–16).

## REFERENCES

1. L. H. Orton and J. C. Needham: *Trans. Inst. Weld.*, 1950, vol. 13, p. 47*s*; 1951, vol. 14, p. 252*s*; 1952, vol. 15, p. 161. *Idem*: Electrical Research Association Report Z/T104, 1955. *Idem*: *Brit. Welding J.*, 1955, vol. 2, p. 419, 506.
2. H. Maecker: *Z. Physik.*, 1955, vol. 141, p. 198.
3. H. Gerdien and A. Lotz: *Z. f. techn. Physik*, 1923, vol. 4, p. 157.
4. G. Busz-Peuckert and W. Finkelnburg: *Z. Physik.*, 1954, vol. 139, p. 212.
5. G. Busz-Peuckert and W. Finkelnburg: *Z. Physik.*, 1955, vol. 140, p. 540.
6. G. Busz-Peuckert and W. Finkelnburg: *Z. Physik.*, 1956, vol. 144, p. 244.
7. G. Busz-Peuckert and W. Finkelnburg: *Z. Physik.*, 1956, vol. 146, p. 655.
8. W. Finkelnburg and H. Maecker: "Handbuch der Physik", 1956, vol. 22, pp. 254–444, Berlin, Springer-Verlag.
9. W. Spraragen and B. A. Lenguel: *Welding J.*, 1943, vol. 22, p. 25.
10. H. Maecker, T. H. Peters, and H. Schenk: *Z. Physik.*, 1955, vol. 140, p. 119.
11. W. Lochte-Holtgreven: *Reports on Progress in Physics*, 1958, vol. 21, p. 312.
12. H. W. Drawin: *Z. Physik.*, 1956, vol. 146, p. 295.
13. H. Goldenberg: *Brit. J. Appl. Phys.*, 1959, vol. 10, p. 47.
14. L. A. King: "Colloquium Spectroscopicum Internationale VI" (Amsterdam 1956), Pergammon Press.
15. L. A. King: *Appl. Sci. Res.*, 1955–6, vol. 5B, p. 189.
16. G. Schmitz: *Z. Physik*, 1952, vol. 132, p. 23.
17. W. Hagenah: *Z. Physik.*, 1950, vol. 128, p. 279.
18. C. G. Suits and H. Poritsky: *Phys. Rev.*, 1939, vol. 55, p. 1184.
19. R. Wienecke: *Z. Physik*, 1955, vol. 143, p. 128.
20. G. Muller and W. Finkelnburg: *Naturwiss*, 1955, vol. 10, p. 294.
21. E. Rohloff: *Z. Physik*, 1949, vol. 126, p. 175, 224.
22. G. E. Doan and R. E. Lorentz: *Welding J.*, 1941, vol. 20, p. 103*s*.
23. J. C. Needham and A. A. Smith: *Brit. Welding J.*, 1958, vol. 5, p. 66.
24. A. A. Smith and P. T. Houldcroft: *Brit. Welding J.*, 1958, vol. 5, p. 421.
25. W. Finkelnburg: "Symposium on High Temperature", 1956, p. 39, Stanford Research Institute, University of California.
26. H. Edels: Electrical Research Association Report L/T230, 1950.
27. R. W. Larenz: *Z. Physik.*, 1951, vol. 129, pp. 327, 343.
28. F. Burhorn, H. Maecker, and T. Peters: *Z. Physik.*, 1951, vol. 131, p. 28.
29. R. M. Gage: U.S. Patent No. 2,806,124, 1957.
30. D. M. Yenni: U.S. Patent No. 2,847,555, 1958.
31. R. Weiss: *Z. Physik.*, 1954, vol. 138, p. 170.
32. Th. Peters: *Naturwiss*, 1954, vol. 24, p. 571.
33. R. Zobel: *Maschinenbau*, 1936, vol. 16, p. 549.
34. J. J. Crowe, G. M. Demming, and J. K. Hamilton: *Welding J.*, 1942, vol. 21, p. 34*s*.
35. M. L. Ghai: "Conference on Extremely High Temperatures", 1958, p. 221, Boston, Chapman and Hall.
36. J. H. Bonin and C. F. Price: "Conference on Extremely High Temperatures", 1958, p. 237, Boston, Chapman and Hall.
37. R. L. Apps and D. R. Milner: *Brit. Welding J.*, 1955, vol. 2, p. 475.
38. A. A. Wells: *Welding J.*, 1952, vol. 31, p. 263*s*.
39. H. C. Ludwig: *Welding J.*, 1957, vol. 36, p. 335*s*.
40. L. B. Loeb: "Fundamental Processes of Electrical Discharges in Gases", 1939, London, Chapman and Hall.
41. T. Wasserab: *Z. Physik.*, 1951, vol. 130, p. 311.
42. W. Weizel and W. Thouret: *Z. Physik.*, 1952, vol. 131, p. 170.

# GAS ABSORPTION FROM ARC ATMOSPHERES

*By G. R. Salter and D. R. Milner*

*The reaction between the high-temperature gases in the arc atmosphere and molten metal has been investigated for the simplest system that could be envisaged, i.e., the absorption of oxygen from an argon–oxygen atmosphere by titanium, the amount of oxygen absorbed being determined by hardness surveys. The effect of welding variables has been investigated and it has been found that the rate of reaction increases with current, arc length, and oxygen partial pressure, and that it is also partly dependent on the condition of the tungsten cathode and the velocity and flow pattern of the gas around the arc. It is concluded that the process controlling the reaction is the rate of diffusion of oxygen across a stagnant gaseous boundary layer adjacent to the metal surface, and that this takes place over an 'active area' in the high-temperature region of the arc. It is postulated that the thickness of the boundary layer is determined by a plasma jet which arises from the constriction of the current at the cathode spot. The magnitude of the high-temperature 'active area' is determined by the current and arc length. An attempt has been made to formulate the quantitative development of this model by considering mass transfer from a hot jet impinging on a plate, in which conventional mass transfer concepts have been applied.*

## Introduction

This work is part of a programme of research into the fundamentals of arc welding, and the first problem was to decide the direction in which effort could most fruitfully be expended. The manner in which welding has been developed to meet the demands made on it has generally meant that an empirical approach had to be adopted, with the consequent neglect of the development of fundamentals; there is thus no lack of basic problems requiring investigation. However, one aspect which appears to be outstanding for its importance and lack of information is gas–metal reactions in arc atmospheres.

The arc is used for welding because it provides an intense heat source that is eminently suitable for the controlled localized melting of metal, so that the conversion of electrical energy into heat and the formation of a weld pool is the primary problem, and this has been the subject of several investigations. Associated with the high-temperature zones in the arc is the potential for increased chemical activity, the control of which has almost entirely determined the rate of development and application of arc welding. In the welding of steel, embrittling reactions delayed the wide-spread use of consumable electrode welding for thirty years until satisfactory coatings had been developed, while for magnesium, aluminium, and the more reactive metals, the general application of arc welding had to await the commercial production of inert gases to provide protective shrouding of the weld pool from the surrounding atmosphere. The number of gas–metal reactions which have required attention is considerable; *e.g.*, porosity in aluminium, copper, and nickel, the embrittlement of titanium, zirconium, beryllium, both porosity and embrittlement in mild steel and hydrogen in low-alloy steels. However, reactions that occur in the high-temperature zones of the electric arc are not always deleterious, and at least part of the action of deep penetration electrodes and of constricted arc cutting is due to the utilization of the heat of recombination, liberated at the metal surface, of molecular gases such as nitrogen, hydrogen, and carbon dioxide, which are in the atomic state in the arc atmosphere.

Despite the importance of these chemico-metallurgical reactions in welding and cutting, no principles of gas–metal reactions in arc atmospheres are known. This is not surprising when the complexity of the conditions existing in the arc and weld pool is considered. Thus, an understanding of the basic principles of the effect of hydrogen in metal arc welds in steel would require a knowledge of the:

(i) Composition of the effective atmosphere in the vicinity of the arc
(ii) Effective temperature of reaction between the arc atmosphere and the weld metal
(iii) Rate at which the reaction occurs at the arc–metal interface
(iv) Fluid flow in the weld pool which transfers the metal that has reacted under arc conditions to other parts of the weld pool, where it will try to attain equilibrium with the new conditions existing there
(v) Behaviour of the gas in the weld pool as it rapidly cools and solidifies.

In addition, these processes are complicated further by the presence of slags and metal globules travelling

Manuscript received 4th November, 1959.
Mr. Milner is in the Department of Industrial Metallurgy at Birmingham University. Dr. Salter, formerly in the same Department, is now a Research Officer with the British Welding Research Association. 

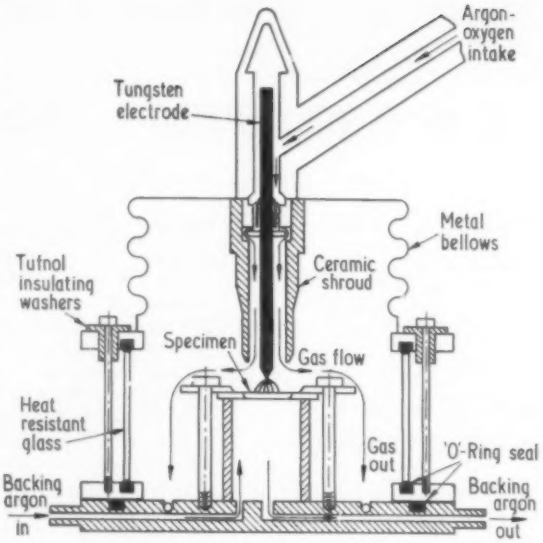
across the arc. There are less complex systems, however, which although of less immediate practical significance are much more suitable for investigation, and the goal that was set for the present work was the examination of the simplest system that could be envisaged to determine the relative influence of the various welding parameters. From this study it was hoped that it would be possible to determine the mechanism of the reaction and to develop a broad pattern of behaviour that would show the processes and factors requiring further consideration. It was desirable that the gas–metal reaction should involve the minimum of complications in the way of porosity and supersaturation, so that the amount of gas that entered the metal could be determined. This meant that the metal had to form a stable complex with the gas, but this in turn meant that the gas would be difficult to extract for analysis. The most convenient system appeared to be oxygen-titanium, since on cooling all the oxygen remains in the titanium, and although it is difficult to extract and measure the amount absorbed, Jenkins and Worner[1] have determined a relation between the hardness of the metal and its oxygen content by adding known quantities of oxygen to titanium. Titanium was therefore melted with an argonarc torch operated in a controlled argon–oxygen mixture and the amount of oxygen absorbed was determined from hardness surveys. In this way the rate of oxygen absorption has been related to the current, arc length, partial pressure of oxygen, gas flow pattern and velocity, and the condition of the electrode.

An analysis of the results suggests that in this system the plasma jet originating at the cathode plays an important part. The jet sucks cold gas into the arc and heats it to form a hot jet impinging on the anode. It is the diffusion of oxygen from this jet across a 'stagnant boundary layer' adjacent to the anode which is the rate-controlling process. A partial theory is presented, formulated in general terms, which should allow an approximate estimation of the amount of gas available for reaction under given conditions for any gas–metal system. To establish and develop this theory, however, it is necessary to have corroborating evidence from systems other than oxygen-argon-titanium. The mode of mass transfer suggested that work on heat transfer in which cold gas is sucked into the arc, heated up, and impinges on the anode in an analogous manner should provide this evidence, and part of the work on heat transfer from arcs reported in another paper in this series[2] was directed to this problem.

## Experimental Work

### Apparatus and experimental technique

The amount of oxygen absorbed in titanium, melted by an electric arc in an atmosphere of argon containing a measured proportion of oxygen, was determined as a function of all relevant variables. An argonarc welding torch with a tungsten cathode was used to melt the titanium, but to prevent atmospheric contamination the torch head with its ceramic shroud was enclosed in a small gas-tight chamber (Fig. 1), comprising brass bellows to allow adjustment of arc length, a cylindrical glass section for viewing the specimen,



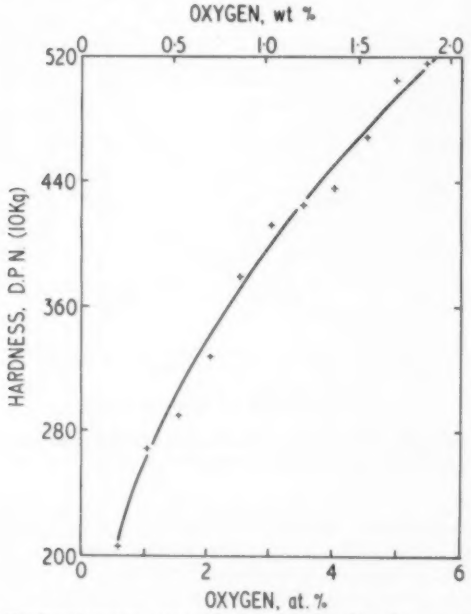

1—*Diagram of controlled atmosphere chamber*

and a base plate through which argon could be lead so as to ensure that no oxygen absorption took place at the rear of the specimen during the melting process. Specimens were 1·25 in. square and with thicknesses between 0·1 and 0·25 in., so that a molten pool could be formed and maintained for 5–30 sec with currents of 50–300 amp. The current was supplied by a commercial drooping-characteristic welding generator, and the arc was ignited by a high-frequency spark. Unless otherwise stated a $\frac{3}{32}$ in. dia. non-consumable thoriated-tungsten electrode was the cathode.

One problem inherent in working with arcs on molten anodes is the measurement of arc length; before these experiments were started the electrode was lowered to touch the specimen and was then raised through the required amount as measured against a vernier scale. However, during operation of the arc above the molten pool of titanium, the arc length was increased by an unknown amount because of the formation of a depression in the pool. The quoted arc lengths are therefore the initial values and not the actual operating ones. Unless otherwise stated the shrouding gas flow rate was 5 litres/min, and control of composition was achieved by a series of rotameters, which were first calibrated against a gas meter so that gas could be supplied and mixed within the range 10 cu.cm to 50 litres per minute with an accuracy of 1% of the flow rate of each gas.

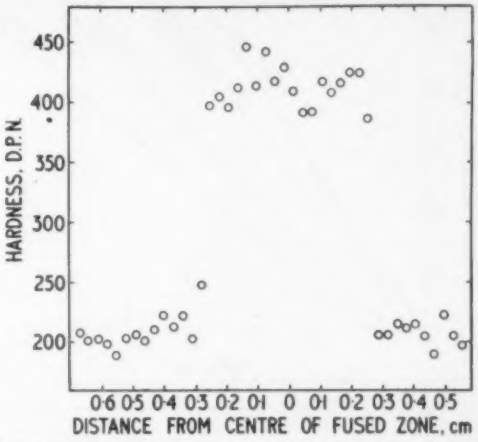
In a typical experiment a titanium specimen was clamped symmetrically on the supporting cylinder, the upper part of the protecting chamber forced onto the O ring in the base plate by compression of the bellows, and the chamber purged of air by passing the required argon–oxygen mixture through the chamber for several minutes. The arc was then struck for the necessary time interval as measured by a stop watch and the specimen was allowed to cool in the chamber with the gas mixture still flowing. To determine the amount of oxygen absorbed the volume of the pool $V$ was

obtained by measuring the upper and lower radii of the fused zone and then treating it as though it were a section of a sphere. The increase in the oxygen content of the fused zone was obtained by determining the increase in hardness and relating it to the oxygen content through the hardness-oxygen relationship of Jenkins and Worner,[1] reproduced in Fig. 2. The total amount of oxygen absorbed $Q$ was then given by: $Q = V \cdot \rho \cdot$ (wt % increase in oxygen content) where $\rho$ is the density of titanium.




2—*Hardness/oxygen concentration relationship for annealed titanium-oxygen alloys. (Jenkins and Worner[1]) (Courtesy Institute of Metals)*

The determination of the increase in oxygen content from the hardness of the fused zone requires some further comment. Previous workers, dealing with the welding of light alloys and of steel with filler rods of a different composition from that of the basis metal, have shown that the mixing in the molten pool is such as to give a uniform chemical composition. In the present work it was found that, whilst there was a distinct difference between the hardness of the fused zone and that of the adjacent unmelted material, there were local variations in hardness, possibly owing to the large grain size and marked anisotropy in the properties of titanium. Individual hardness determinations were therefore inadequate, and hardness traverses were made across the centre of each specimen and the mean increase in hardness was determined. By making several such traverses across different sections and at different depths of the same specimen no tendency for a preferential distribution of oxygen could be found, and the mean value of hardness increase, as determined by a single hardness traverse, agreed well with the increase determined from a more thorough survey. Figure 3 shows the results of a typical traverse, in which hardness measurements were made every 0·030 in. with a 10 kg load. Although the local hardness variations are very apparent, the only significant trend is that of a transition region extending through the fused–solid interface between the two zones of markedly different hardness.




3—*Typical result of hardness traverse across section of titanium specimen, showing marked difference between hardness of fused and unmelted metal, and comparative uniformity of fused region*

## Results

Using the technique described, an examination was made of the variation of the amount of gas absorbed with time, current, oxygen partial pressure, arc length, gas flow pattern, and changes in the electrode.

### Rate of increase of oxygen absorption with time

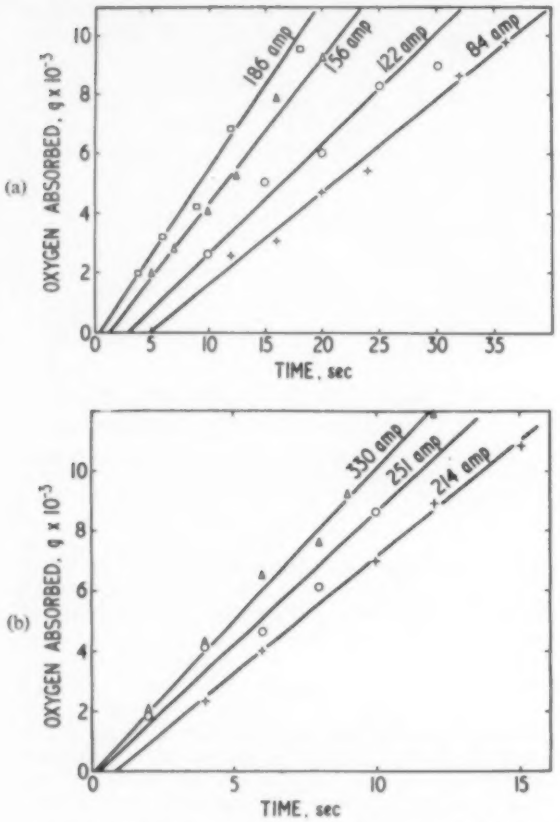
The amount of oxygen absorbed as a function of time for seven values of the current, but with constant oxygen partial pressure and arc length, is shown in Fig. 4. In each case the amount of oxygen absorbed increased linearly with time, while the rate of absorption increased with current, but the curves did not extrapolate back to zero absorption at zero time. The explanation for this is of some interest; the rate of oxygen absorption will be very rapid only in the relatively small high-temperature zone of the arc which is at a sufficiently high temperature for the oxygen to be dissociated; but for the oxygen to be rapidly absorbed into the metal adjacent to this region it is necessary for the metal to be molten. After the arc is struck it takes a finite time for a molten pool to be formed, and this time will decrease (as does the intercept on the ordinate) as the current increases, so that the intercept gives an indication of the time required for the formation of a molten pool of metal having the same diameter as the arc.

### Effect of oxygen partial pressure

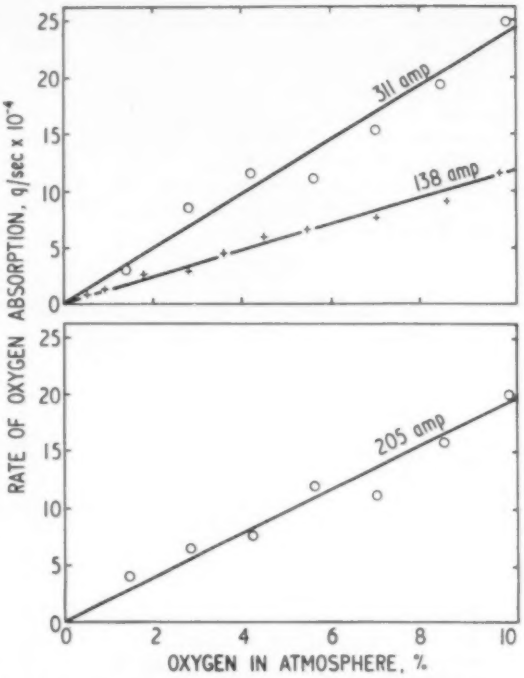
With increases of the oxygen partial pressure up to 10% the amount of oxygen absorbed into the titanium was found to increase linearly as shown in Fig. 5.

### Effect of arc length

Changing the arc length was found to affect the oxygen absorption in a complex and haphazard way,




4—*Variation of oxygen absorption with time:* (a) *84–186 amp;* (b) *214–330 amp. Atmosphere argon/2·8% oxygen. Arc length 0·4 cm*




5—*Variation of rate of oxygen absorption with amount of oxygen added to the shrouding atmosphere. Arc length 0·3 cm*

which could not at first be understood. As shown by the results in Fig. 6 there was a general tendency for an increase in absorption until a critical arc length had been reached; above this, approximately constant absorption took place. The postulated explanation for this behaviour is that the arc area over which the absorption took place increased with arc length, thus increasing the rate of absorption. However, when this area exceeded the area of the molten pool no further increase in absorption would be expected.

#### Influence of gas flow conditions around the arc

The increase in the rate of oxygen absorption with increased time and partial pressure of oxygen, when further oxygen is presented to the metal surface, suggests that the rate controlling process does not lie in the absorption of the oxygen by the metal but in the rate at which the atomic oxygen is supplied to the metal surface. Thus the problem is probably one in which mass transfer through the gas is the rate-controlling process, and, if this were so, then changes in the gas flow pattern around the arc would be expected to have an influence. A correlation between the gas flow and the rate of absorption was sought by examining the effect of changes in the diameter of the ceramic shroud, the height of the shroud above the specimen, the influence of gas velocity, and the removal of the ceramic shroud. The results shown in Fig. 7 indicate that the removal of the shroud and variations in its height and diameter had an effect, but did not change the amount of gas absorption by more than 25–50% even in the extreme case of the removal of the shroud, which should have had a very marked effect on the direction of the gas flow. These changes in the geometry of flow are difficult to analyse: the effect of velocity is more amenable, but changing this variable by a factor of sixty did not result in any significant difference in the rate of absorption. As will be shown later, for an increase in the velocity by a factor of sixty, conventional mass transfer theory would predict an eightfold increase in the rate of mass transfer.

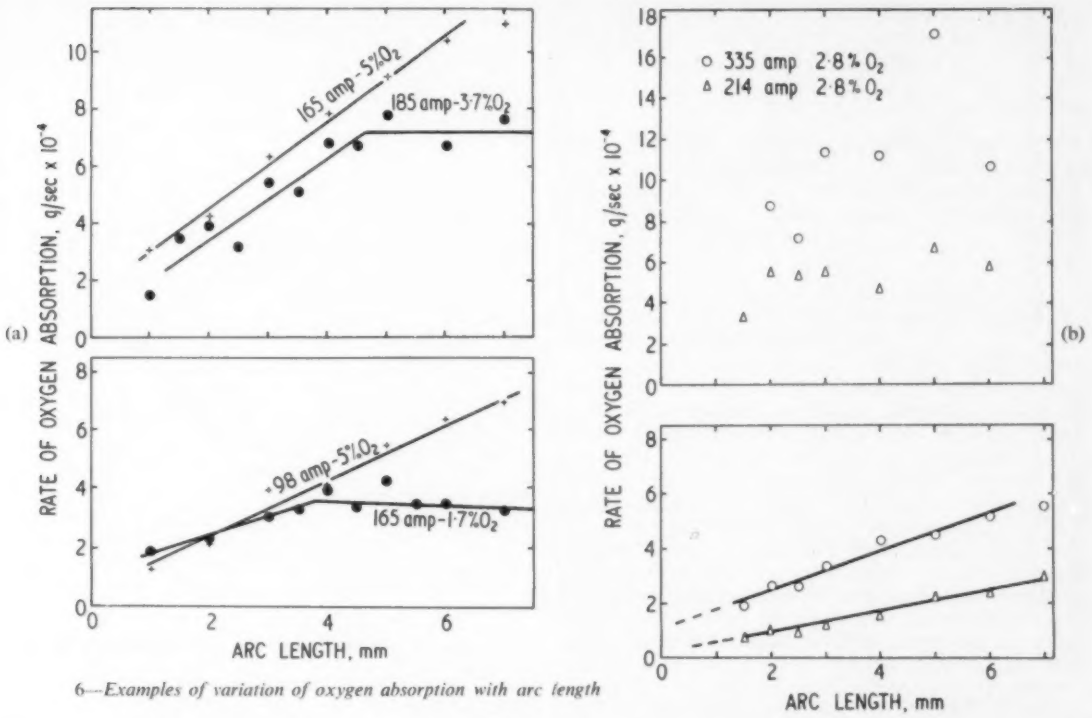
The interpretation of the effect of changes experienced with variations in the gas flow conditions has involved some difficulty, because of the number of factors that could be involved. For example, since the

**Table I**

**Comparison of rate of oxygen absorption between overhead and downhand positions**

Atmosphere argon/4% oxygen; current 117 amp; ⅜ in. dia. ceramic nozzle; arc length 0·3 cm

| *Shrouding Gas Flow Rate, litres/min* | *Rate of Oxygen Absorption, g/sec × 10⁻⁴* | |
|---|---|---|
| | *Downhand* | *Overhead* |
| ½ | 4 | 3·2 |
| 1 | 4·8 | 2·6 |
| 21 | 4·6 | 3·5 |




6—*Examples of variation of oxygen absorption with arc length*

arc is at a very high temperature, rapid convection currents could be expected. Any such influence was investigated by comparing rates of oxygen absorption, when the torch and gas stream were pointing vertically downwards, with similar results when the apparatus was inverted. The results presented in Table I show that less gas was absorbed when the torch was pointing vertically upwards.

#### Influence of non-consumable cathode

During the course of this work it was sometimes found desirable to repeat or extend the range of the investigation, but when this was attempted it was found that the results were often not reproducible; whilst the effect of a particular variable on the rate of gas absorption always showed the same qualitative trend, the absolute magnitude often differed. It was therefore concluded that another factor must be exerting an influence, and by process of elimination it was decided that this could only lie in some change in the nature of the cathode. The cathode generally used in this work comprised thoriated tungsten rod as supplied by the manufacturer, the thoria content being of the order of 2%. To examine the possibility of the cathode exerting an influence, the rate of gas absorption was determined under standard conditions for seventeen electrodes selected from tungsten, zirconiated tungsten, and two grades of thoriated tungsten. A considerable scatter of results was obtained, as shown in Table II. Since the variation between different electrodes was so large, the possibility of variations within an individual electrode also had to be considered. One thoriated tungsten electrode that was particularly suspect was therefore examined at both ends, the standard experiment being repeated seven times with the electrode shortened by $\frac{1}{2}$ in. between

**Table II**

**Comparison of the rate of oxygen absorption for various electrodes**

Atmosphere argon/2% oxygen; current 117 amp; arc length 0·3 cm; gas flow rate 5 litres/min

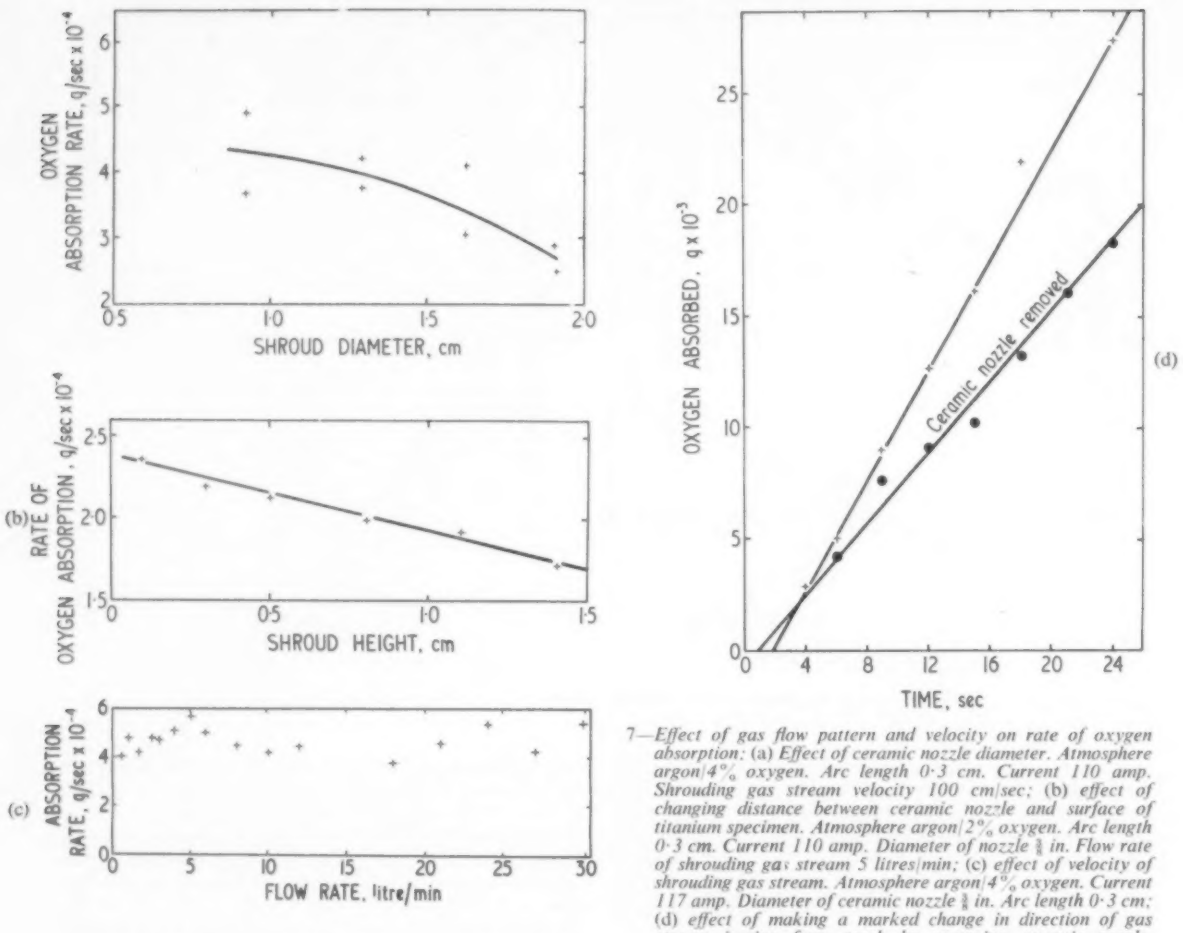
| *Electrode* | *Rate of Oxygen Absorption, g/sec × 10⁻⁴* | | |
|---|---|---|---|
| Thoriated tungsten, type 1 | 1·9 | 1·9 | 2·0 |
| | 2·1 | 2·0 | 2·3 |
| Thoriated tungsten, type 2 | 2·1 | 2·2 | 1·8 |
| | 2·0 | 2·1 | 2·8 |
| Tungsten | 2·0 | 2·4 | |
| Zirconiated tungsten | 1·6 | 1·9 | 2·0 |

**Table III**

**Variation of the rate of oxygen absorption obtained with one thoriated tungsten electrode**

Atmosphere argon/2% oxygen; arc length 0·3 cm; current 117 amp; gas flow rate 5 litres/min

| *Test No.* | *Distance from Reference End of Electrode in.* | *Rate of Oxygen Absorption, g/sec × 10⁻⁴* |
|---|---|---|
| 1 | 0 | 1·9 |
| 2 | 0·5 | 2·0 |
| 3 | 1·0 | 1·8 |
| 4 | 1·5 | 2·0 |
| 5 | 5·0 | 2·6 |
| 6 | 5·5 | 2·4 |
| 7 | 6·0 | 2·1 |




*7—Effect of gas flow pattern and velocity on rate of oxygen absorption:* (a) *Effect of ceramic nozzle diameter. Atmosphere argon/4% oxygen. Arc length 0·3 cm. Current 110 amp. Shrouding gas stream velocity 100 cm/sec;* (b) *effect of changing distance between ceramic nozzle and surface of titanium specimen. Atmosphere argon/2% oxygen. Arc length 0·3 cm. Current 110 amp. Diameter of nozzle ⅜ in. Flow rate of shrouding gas stream 5 litres/min;* (c) *effect of velocity of shrouding gas stream. Atmosphere argon/4% oxygen. Current 117 amp. Diameter of ceramic nozzle ⅜ in. Arc length 0·3 cm;* (d) *effect of making a marked change in direction of gas stream issuing from torch by removing ceramic nozzle. Atmosphere argon/4·4% oxygen. Arc length 0·4 cm. Current 149 amp*

each test. As shown in Table III, a range of results was obtained with a variation between minimum and maximum of 44%, which was of the same order as the variation between different types of electrodes. Clearly, if variations of this extent occured throughout the work then much greater scatter would have been expected than was in fact obtained in the results given in the previous figures. A further experiment was therefore made in which the standard test was repeated three times for exactly the same setting of one electrode and with that electrode operating an arc continuously for 17 min between two tests. The results (Table IV)

**Table IV**

**Degree of reproducibility obtained with one thoriated tungsten electrode**

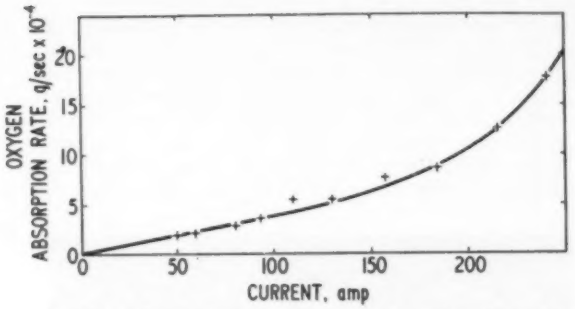
Atmosphere argon/2% oxygen; arc length 0·3 cm; current 117 amp; gas flow rate 5 litres/min

| *Test No.* | *Rate of Oxygen Absorption, g/sec* × $10^{-4}$ |
|---|---|
| 1 | 1·6 |
| The electrode was then operated for 17 min, then: | |
| 2 | 1·7 |
| this was repeated, then: | |
| 3 | 1·7 |

showed that, if the electrodes were not changed or the end interfered with between tests, reproducible results were obtained, even with prolonged operation of the arc. Only results obtained with constant electrode condition for each series of tests have been presented in Figs. 3–7.

**Relation between current and rate of gas absorption**

The arc current is clearly an important variable, and it was one of the first to be examined. But, although an increasing trend was apparent no quantitative relationship could be established because of the scatter of experimental results. The reason for this became clear when it was realized that changes in the cathode could exert a marked influence, since in normal practice the cathode is changed for one of larger diameter when the current is much increased. However, by careful attention to detail and for the short time necessary at high currents it was found possible to cover a current range of 50–300 amp with a $\frac{5}{32}$ in. dia. electrode (Fig. 8). One further difficulty was encountered in examining the effect of current, in that an initial period




8—*Effect of current on rate of oxygen absorption. Atmosphere argon/4% oxygen. Arc length 0·3 cm. Time of absorption 10 sec*

which varied markedly over the current range investigated, was required for a molten pool to be established to a size at which the rate of gas absorption became constant. This was overcome by controlling the gas flow system by means of solenoid-operated valves, in such a way that the molten pool could first be established in an atmosphere of pure argon, and the oxygen–argon mixture then switched in for the required length of time.

### Phenomenological Interpretation of Results

It is now proposed to attempt a qualitative interpretation of the results in an effort to establish the mechanism that controls the rate of reaction. Since the amount of oxygen absorbed continues to increase linearly with time, and also with increasing oxygen partial pressure, it would appear that all that arrives at the surface of the titanium is absorbed, in which case the controlling factor is the rate at which the oxygen arrives at the surface of the metal. Thus the problem becomes one of mass transfer in the arc atmosphere. Gas–solid reactions in general form part of the field of fluid dynamics and there is no reason to believe that the concepts which have been evolved will not apply in this case, although the presence of the arc necessitates differences in the formulation of the problem. The gas at a distance from the metal surface is in rapid motion, but at the metal surface gas molecules or atoms must be stationary (or moving with the relatively low velocity of the liquid metal). In the gas which is in rapid motion there is no difficulty in the transport of the oxygen–argon mixture, but adjacent to the metal surface there is a transition layer in which the velocity of the gas changes from its high bulk value to the near zero value at the metal surface. As the metal surface is approached through this boundary layer, the part played in transport by macroscopic motion decreases and diffusion becomes the dominant process. The oxygen in the boundary layer is depleted by absorption into the titanium and it is the continued supply by diffusion that limits the rate at which the oxygen arrives at the titanium surface. When analysing problems of this nature it is common practice to replace the transition layer by an 'equivalent stagnant layer'. Then if the thickness of the layer is $x$ cm, the concentration of oxygen in the bulk of the gas $c$, and it is assumed that at the titanium surface the oxygen concentration is of the order of the dissociation pressure of $TiO_2$ ($10^{-12}$ atm and therefore negligible) then the rate of diffusion $q$ across the stagnant boundary layer is given by Fick's law:

$$q = -D\frac{dc}{dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where $D$ is the coefficient of diffusion of oxygen through argon, and $dc/dx$ is the concentration gradient. Reformulating in terms of the oxygen partial pressure $p$, and assuming a linear change in concentration through the stagnant layer:

$$q = \frac{-D}{RT}\frac{dp}{dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $R$ is the universal gas constant and $T$ the absolute temperature.

This model is in accord with the experimental determination of the effect of time and oxygen partial pressure, which both result in a linear increase of oxygen absorption. However, the gas velocity should also have a marked effect on the thickness of the boundary layer and hence on the rate of reaction, which will later be shown to be proportional to the square root of the velocity. But changes in the velocity of gas flow through the ceramic shroud had only a comparatively small effect, as did marked alterations in the gas flow pattern. If the boundary layer model is valid, it implies that the gas flow in the high-temperature reacting region is independent of the imposed shrouding gas velocity. Convection was shown to have only a limited influence by the experiments in which the apparatus was inverted. The conclusion therefore was that plasma jets probably existed in the arc, and since Maecker[3] has shown these to have velocities of the order of $10^4$ cm/sec, the influence of the shrouding gas with velocity of the order of $10^2$ cm/sec would be negligible by comparison. Wilkinson and Milner[2] have subsequently sought and found plasma jets in argon arcs of this type, and have shown that their velocities are of the same order as those found by Maecker for the carbon arc in air. It can therefore be concluded that the results on the effect of changes in shrouding gas velocity are not incompatible with the boundary layer model. The influence of the tungsten cathode follows directly from this argument since the rate of reaction depends on the velocity of the plasma jet. This in turn is determined by the size of the cathode spot, which is clearly likely to vary from one electrode condition to another, probably being related to the thoria distribution.

The variables which remain to be explained are the arc length and current, and for these it is necessary to consider the area over which the reaction takes place.

#### 'Active Area' of reaction

The increase in the amount of oxygen absorbed with time (Fig. 4) showed that there was an initial period, while the weld pool was being formed, during which the rate of gas absorption was less than that with a fully formed pool. However, once the constant rate of gas absorption was attained it was not influenced by a further increase in the size of the weld pool. The explanation for this result is related to the size of the plasma jet, which forms an intense high-velocity, high-temperature inner core to the arc, raising the rate of reaction where it impinges on the anode. As the arc length is increased the plasma jet velocity attenuates[4]

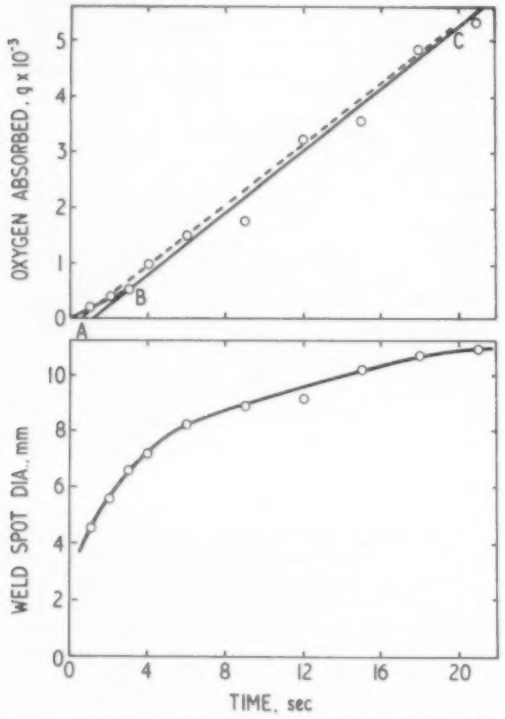
and it broadens out[2] to increase the 'active area' until an arc length is attained at which the active area equals the size of the weld pool. A further increase in arc length then produces no change in the rate of oxygen absorption, which is in general agreement with the experimental results shown in Fig. 6. A determination of the size of the active area can be made by measuring simultaneously the rate of increase of gas absorption and the increase in diameter of the weld pool with time; when the rate of gas absorption becomes constant the active area is equal to the size of the molten pool. Unfortunately the accuracy of this method is critically dependent on the scatter in the experimental measurements. The best set of results that could be obtained are reproduced in Fig. 9. This shows that the diameter of the active area could lie anywhere between the value given by the minimum intercept on the time axis (4 mm) and the value at the change in the slope of the curve *OBC* (6·5 mm). In the absence of more accurate information the diameter of the active area for this case will therefore be taken as approximately 5 mm. For a corresponding arc with a water-cooled copper anode, Wilkinson and Milner found the diameter of the plasma jet to be 0·16 cm, from which it appears that for these conditions the jet exerts an influence over a distance of the order of $2\frac{1}{2}$–4 times its own diameter.

To obtain some indication of the variation of the active area with arc length and current an indirect approach had to be adopted, in which changes in the luminous area were measured photographically. The equipment and technique developed by Wilkinson and Milner[2] was used. Firstly, a photograph was taken of the 100-amp arc on titanium in an atmosphere of argon/4% oxygen (Fig. 10), which corresponds to the conditions for which an estimate was made of the active area from the time curve. The maximum luminous width was found to be 1 cm in diameter compared with the estimate of the active area of

10—*Photograph of 100-amp arc between tungsten cathode and molten titanium anode in atmosphere of argon/4% oxygen. Arc length 0·3 cm*

0·5 cm. It was assumed that changes in the luminous area at the anode would reflect changes in the active area, and an examination was made of the effect of arc length and current on the luminous area, with the results shown in Figs. 11 and 12. The luminous area increases in both cases, and it was therefore concluded that a similar increase in the active area was responsible for the increase in oxygen absorption shown in Figs. 6 and 8.

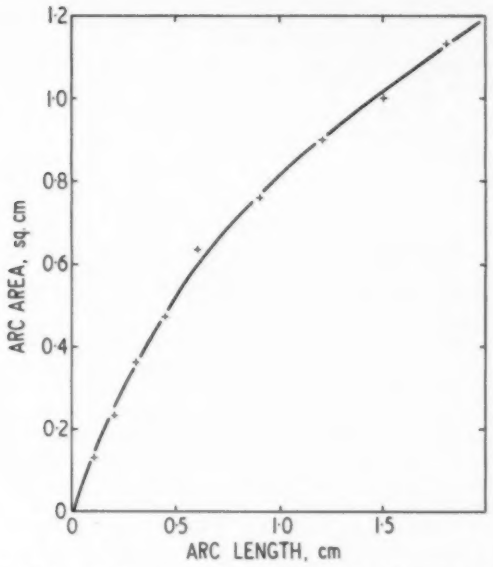
An examination was also made of the effect of shrouding gas flow rate on the size of the active area, but except for a small change at low rates this had no effect (Fig. 13).



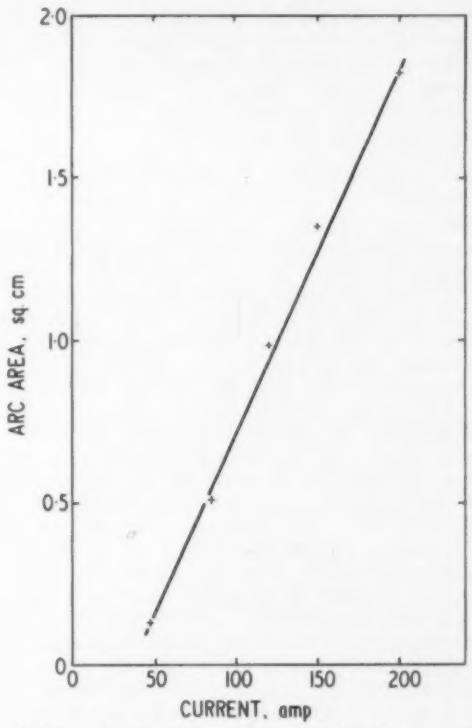

9—*Variation of oxygen absorption and diameter of fused zone with time. Atmosphere argon/4% oxygen. Current 110 amp. Arc length 0·3 cm*

### Theoretical Development of Mass Transfer Model

In the previous section it has been shown that the process that controls the rate of oxygen absorption into titanium is, in all probability, the diffusion of oxygen through a stagnant boundary layer immediately adjacent to the molten metal. So that the results of this work should be applicable to other arc atmosphere–metal reactions it is necessary to develop the qualitative model as postulated and to establish a quantitative theory. This is difficult. Conditions in the active area are far from homogeneous, since the temperature can vary from 20,000°C. at the centre of the arc to about 3,000°C. at the periphery of the active area, whilst the reacting gas can be in the molecular



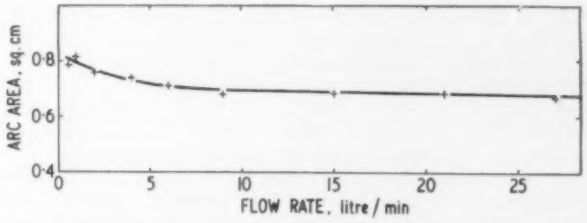

11—*Variation of area of arc close to anode with arc length. Current 100 amp*




12—*Variation of area of arc close to anode with current. Arc length 0·9 cm*

or atomic state according to the effective temperature of the boundary layer. In addition, the plasma jet velocity varies across the arc and it is probable that at the anode spot the metal is near or at its boiling point, causing the gas composition to change markedly by the inclusion of metal vapour. In the present paper it is only possible to develop the theoretical approach in terms of uniform conditions; *i.e.*, a mean velocity and a mean temperature.

One method of approach to the problem of arc atmosphere–metal reactions is to consider that the arc provides a high-temperature jet of gas, and then to apply the conventional gaseous mass transfer analysis to the reaction between this gas stream and the molten metal. The effect of the arc is then introduced by the influence it has on the temperature of the gas, by the magnitude of the active area which it creates, and the velocity of the electromagnetically generated plasma jet.




13—*Variation of arc area with flow rate of shrouding gas stream. Current 100 amp. Arc length 0·9 cm*

Following the conventional treatment of gaseous mass transfer problems the rate of reaction $Q$ is made proportional to the change in concentration $\Delta c$, of the reacting constituent

$$Q = h_m \Delta c A \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where $h_m$ is the mass transfer coefficient and $A$ the area over which the reaction takes place. The mass transfer coefficient $h_m$ is related to the properties of the gas and the system by three dimensionless groups according to:

$$Nu = f(Sc \,.\, Re) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where $Nu$ is Nusselt's number, $Sc$ is Schmidt's number and $Re$ is Reynold's number.

Inserting quantities for the dimensionless groups

$$\frac{h_m d}{D} = f\left(\frac{\eta}{\rho D}\right)\left(\frac{\rho v d}{\eta}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where $d$ is the diameter of the jet, $\eta$ is the gas viscosity, $\rho$ is the density of the gas, and $v$ is the velocity of the gas stream.

The problem now is to determine the form of the function. In many cases equation (5) can be written as

$$\frac{h_m d}{D} = k\left(\frac{\eta}{\rho D}\right)^{\frac{1}{3}}\left(\frac{\rho v d}{\eta}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

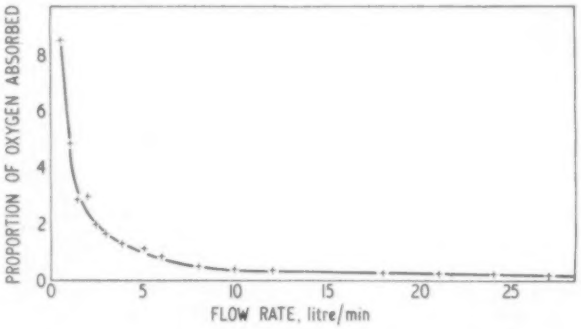
where $k$ is a constant. As far as the authors know, no experimental examination has been made of mass transfer from a jet, but Woodrow[5] kindly carried out a

theoretical analysis in which he solved the Navier-Stokes equation with some approximations, and arrived at the conclusion that $k$ was 0·8, with a possible error of 40% for a distance of about twice the jet radius for the stagnation point.
Thus, from equations (3) and (6):

$$Q = \frac{0{\cdot}8D\Delta cA}{d}\left(\frac{\eta}{\rho D}\right)^{\frac{1}{3}}\left(\frac{\rho vd}{\eta}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots \quad (7)$$

From this equation it is possible to calculate the rate of oxygen absorption and to compare it with the experimental values. The 110-amp arc with 4% oxygen in the shrouding atmosphere will be considered, for which the diameter of the active area has been estimated as 0·5 cm. For this arc Wilkinson and Milner[2] have found the diameter of the cathode plasma jet to be about 0·16 cm, and the velocity at the anode $2{\cdot}7\times10^4$ cm/sec. The difficult factor to estimate is the temperature, and this determines the values of $D$, $\rho$, and $\eta$. At present only a guess can be made, and a value of 5,000°C. will be taken. This value is chosen on the argument that Busz-Peuckert and Finkelnburg's[6,7] measurements of the temperature in the column of the argon arc suggest that for the case in question it would probably be of the order of 12,000°C. at the arc axis adjacent to the anode, and the active area would be expected to terminate around the 4,000°C. isotherm where dissociation markedly decreases, giving a mean arc temperature of 8,000°C. The titanium is at a temperature somewhat above its melting point, say 2,000°C., and thus the mean boundary layer temperature is 5,000°C. The value of the coefficient of diffusion for atomic oxygen in argon at 5,000°C. is not known, but it should lie between the coefficient of self diffusion of argon (27 sq. cm/sec)[9] and that for neon (61 sq. cm/sec)[9] so that a value of 45 sq. cm/sec will be assumed. The viscosity $\eta$ is $18\times10^{-4}$ poises,[9] the concentration of oxygen in the shrouding atmosphere is $3{\cdot}4\times10^{-6}$ g/cu.cm and $\rho=1{\cdot}04\times10^{-4}$ g/cu.cm. Inserting these values in equation (7), the rate of oxygen absorption is found to be $1{\cdot}7\times10^{-3}$ g/sec, which is four to five times the experimentally determined value of $3\text{–}4\times10^{-4}$ g/sec (depending on the condition of the cathode tip). This theoretical overestimation is due to the application of equation (7) over a larger area than that for which it was derived. The absorption of oxygen is rapid at the centre of the jet where it impinges on the anode, but as the jet splays out along the surface of the anode, and the distance from the stagnation point increases, the gas is impoverished of oxygen, and the rate of absorption must decrease. Thus equation (7), which Woodrow derived for application to an area extending over twice the radius of the plasma jet from the stagnation point, could not be expected to hold for the larger area to which it has been applied. This point becomes particularly clear when the total amount of oxygen being transported by the plasma jet is considered. Taking again the case of the 110-amp, 3-mm arc, using Wilkinson and Milner's figures for the jet diameter and velocity, and assuming the jet temperature to be between 10,000° and 15,000°C. (say 12,500°C.) then the jet transports $7{\cdot}5\times10^{-4}$ g of oxygen towards the anode per second. That is, less than half the theoretically predicted quantity absorbed. The experimental measurements show that one half of the oxygen transported by the jet is absorbed in this particular case. The refinement of the theory presents considerable difficulty with the knowledge available, and it is probably better to follow a combined experimental and theoretical approach in which, instead of calculating the rate of a gas absorption for any particular system directly from equation (7), the corresponding data for the oxygen–titanium system is converted by relating it to the diffusivity, density, and viscosity of the system according to equation (7). The problem of assigning correct values to the gas constants could also involve some error. This could be particularly true for the coefficient of diffusion, which is very difficult to estimate and determines the rate of absorption according to the $\frac{2}{3}$ power. The density is much less of a problem, and in any case only enters as a $\frac{1}{2}$ power. Viscosity is again a difficult property to estimate, but has only a small effect, determining the rate of absoprtion as the $\frac{1}{6}$ power.

It is of some interest to compare the contribution of the plasma jet to the rate of mass transfer, with a system in which no jet operates, and in which the rate of reaction is determined by the relatively slow shrouding gas stream. Then the insertion of the relevant values in equation (7) shows that the rate of absorption would be about 10% of that in the presence of the plasma jet. For the 110-amp arc already considered, with the gas shrouding flow rate of 5 litres/min, about 10% of the total oxygen flowing through the ceramic nozzle was absorbed by the titanium. At lower shrouding gas velocities the plasma jet action was extremely efficient in transferring oxygen to the titanium, as illustrated by Fig. 14, in which the rate of absorption (determined as a function of the shrouding gas velocity, Fig. 7*c*) has




14—*Variation of efficiency of oxygen transfer to titanium with velocity of shrouding gas stream. (Replot of data given in Fig. 7c)*

been replotted as a proportion of the total oxygen passing through the shroud. At a flow rate of 0·5 litres/min 85% of the oxygen entered the titanium, but at this low flow rate the pumping action of the plasma jet, which transports 540 cu.cm of gas per sec at 15,000°C. (*i.e.*, $18{\cdot}8\times10^{-3}$ g/sec) is greater than the flow rate of 8 cu.cm of gas at N.T.P. ($13{\cdot}9\times10^{-3}$ g/sec) which passes through the ceramic shroud. It is therefore probable that in the lower range of flow rate some of the gas in the chamber recirculated through the arc. Welding a reactive metal like titanium, in an enclosed chamber without a gas flow, should result in efficient gettering of the atmosphere which must be continuously pumped through the arc by the plasma jet.

There is one further point of interest about equation (7) and this relates to the influence of current, which was not entirely explained by the change in the active area. Measurements of the luminous area show a lower rate of increase with current (Fig. 12) than the rate of oxygen absorption (Fig. 8). However, as the current is increased, both the diameter and velocity of the plasma jet increases, and equation (7) shows that these have to be taken into account as $(v/d)^{\frac{1}{2}}$. Wilkinson and Milner's measurements of plasma jet characteristics for an argon arc operating on a water-cooled copper anode show that the jet velocity increases with current more rapidly than its diameter, and support the general plausibility of this explanation for the increase in the rate of oxygen absorption.

## Discussion

It is now necessary to discuss the progress that has been achieved in relation to the initial aim of the research. The intention was to investigate one simple arc atmosphere–metal reaction so as to determine the effect of welding parameters and establish the mechanism of reaction. The titanium–oxygen–argon system was chosen for experimental convenience and analysis of the results led to the hypothesis that the rate-controlling process was the diffusion of oxygen across a stagnant boundary layer of gas adjacent to the molten metal. There are three aspects of the work which can be discussed: the development of the theoretical explanation of the experimental results; the relationship between the titanium–argon–oxygen system and other gas–metal systems; and the relationship between this work and the welding problems of embrittlement and porosity.

It has been shown that the basic process is gaseous mass transfer, and an attempt has been made to apply the principles of this subject in the form in which they have been developed for application to the conventional problems of fluid dynamics. Unfortunately the arc welding system is complex and a large gap has to be bridged between the established cases for which adequate data are available and the arc–metal reaction systems. The authors have used an approach in which the arc is regarded as producing a jet of hot gas, and the reaction between the jet and the metal is considered. However, the basic system of a jet acting on a plate has not been investigated, so that equations (6) and (7) cannot be regarded as established, even for systems in which no arc operates, although their general formulation is correct. The next step in the development of this approach is the introduction of the arc parameters. These enter in three respects: firstly, the diameter and velocity of the jet are dependent upon the variation in current density; secondly, the active area over which the reaction takes place is determined by the current and arc length; and finally, the temperature of the boundary layer is related to the energy expended in the arc. If equations could be formulated to relate these factors then $d$, $v$, and $A$ could be eliminated from equation (7) and the rate of reaction would then be determinable in terms of the properties of the gases and measurable welding parameters, *e.g.*, current and arc length. To do this, however, considerably more theoretical and experimental work will have to be carried out on plasma jets, the energy balance of the free burning arc column, and the interaction of the arc column with a plate electrode, which means that an exact interpretation of the experimental results given in this paper is probably some way off. Nevertheless it is possible to use these results and the partial theory without this complete interpretation.

The theory as developed is independent of the specific titanium–argon–oxygen system from which it was derived, but a generalization of this nature requires supporting evidence from other systems, and part of the work of Wilkinson and Milner on heat transfer, presented in another paper in this series, has been aimed at producing this evidence. The relationship between heat and mass transfer lies in the similarity of the transport process. In mass transfer, cold atoms or molecules from the surrounding atmosphere are sucked into the arc, raised to a high temperature, and transported to the molten pool, where they react with the metal. Similarly, when no reaction occurs, heat is transferred to the weld by gas atoms and molecules which are drawn into the arc, heated up, and then impinge on the weld to give up part of their energy. Wilkinson and Milner have endeavoured to separate this plasma-jet heating from the electron heating and find that the results can be interpreted by a similar mechanism and theory to that proposed in this paper for mass transfer. If it is assumed that the theoretical interpretation is justified, then the rate of reaction for any other gas–metal system is related to that determined for oxygen in titanium by the diffusivities, viscosities, and densities according to equation (7). However, not all gas–metal systems are of the same type as oxygen–titanium; oxygen has a high solubility in titanium, but in many other cases (*e.g.*, hydrogen in steel or aluminium) there is a much lower solubility limit, and for these systems equation (7) can only predict the rate at which the reacting gas will arrive at the metal surface. Whether or not it will be absorbed will depend on the amount of gas already in the metal and the solubility limit for the conditions of temperature and pressure existing at the reacting surface.

The practical welding problems in which gas absorption can be important are embrittlement and porosity. If embrittlement is the difficulty, and the amount of absorbed gas which can be tolerated without undue deterioration of the metallurgical properties is known, then the purity of the effective atmosphere which has to be maintained should be calculable from the titanium results. In this respect, plasma jets probably play an important part in determining the relationship between the shrouding gas composition

and that which is effective in the arc area (see ref. 8 for further discussion of this point). Much further information is required to deal with the general problem of porosity. Thus, although equation (7) will provide an estimate of the amount of gas arriving at the surface, it is necessary to know the effective temperature at the surface to obtain the solubility limit for the conditions under which absorption takes place. Metal which absorbs gas according to these conditions is then transported to other parts of the weld pool by the general mixing action that takes place, and it then attempts to achieve equilibrium at the new conditions, either retaining the gas in super-saturated solution, or rejecting it to cause porosity. To pursue this problem it is therefore necessary to know more about the effective temperature of reaction and of movement and cooling in the weld pool. It is intended to investigate some of these problems in future researches.

In conclusion, it should be stated that the arc–metal reactions which have been deleterious in welding may possibly be turned to advantage in other fields. Thus nitric acid has been made for many years by passing air through the arc to form nitrogen oxides, which are then 'quenched' and dissolved in water.[10] There is also the Shear-Korman process[11] for the extraction of beryllium, in which two electrodes are formed of beryl ore mixed with crushed coal; these are continuously consumed in an arc furnace in which the ore material is broken down into its elements and ejected at high speed from the arc into the atmosphere as a long flaming jet. Chlorine gas is simultaneously fed into the furnace and mixes with the vapour jet and as it cools it converts the metallic constituents of the ore to their chlorides. The chloride vapours are piped to a series of condensing chambers in which each of the different chlorides is successively condensed and the beryllium is then extracted from its chloride by electrolysis. However, for reasons unknown to the present authors this process has not been developed for commercial usage. In another attempt to carry out chemical reactions in the high-temperature zones of the arc, zirconium iodide vapour was passed through an arc between a tungsten electrode and a zirconium ingot contained in a water-cooled copper mould.[19] The ingot grew by deposition of zirconium from the dissociated zirconium iodide, and the iodine vapour was pumped off. Zirconium chloride and zirconium bromide could not however be dissociated in this manner.

With the growing interest in the physics and chemistry of high temperatures, and the fact that only the electric arc provides a means of creating sustained temperatures in the region 4,000°–50,000°C., it is possible that the field of high-temperature arc reactions may extend in importance beyond the immediate applications to welding and cutting.

## Conclusions

(1) The rate of absorption of oxygen by titanium increases with current, oxygen partial pressure, and arc length, and is also to some extent dependent upon the condition of the tungsten cathode and the velocity and flow pattern of the gas around the arc.

(2) The process which controls the reaction is the rate of diffusion of oxygen across a stagnant gaseous boundary layer adjacent to the metal surface, and this takes place over an 'active area' in the high-temperature region of the arc.

(3) The thickness of the boundary layer is determined by the velocity of a plasma jet, which arises as the result of the constriction of the current at the cathode spot.

(4) The magnitude of the high-temperature 'active area' is related to the current and arc length.

(5) The quantitative development of conclusions (2)–(4) has been attempted by the application of conventional mass transfer principles to the system of a hot jet impinging on a plate.

## Acknowledgments

This work is part of a programme of research into some aspects of the joining of metals which is being carried out at the Department of Industrial Metallurgy at the University of Birmingham. The authors wish to thank Professor E. C. Rollason, Head of the Department, for his interest and encouragement throughout the course of this work, and the Director of the United Kingdom Atomic Energy Authority at Harwell for financial support. They are also indebted to Dr. J. Woodrow of the Reactor Division at Harwell for informative discussions on heat and mass transfer and for his solution of the problem of a jet impinging on a plate, and to their colleague J. B. Wilkinson for the stimulation that arises from constant discussions of problems of mutual interest.

## REFERENCES

1. A. E. Jenkins and H. W. Worner: *J. Inst. Metals*, 1951, vol. 80, p. 157.
2. J. B. Wilkinson and D. R. Milner: *Brit. Welding J.*, 1960, vol. 7, p. 115 (this issue).
3. H. Maecker: *Z. Physik*, 1955, vol. 141, p. 198 (see also ref. 8).
4. R. Wienecke: *Z. Physik*, 1955, vol. 143, p. 128.
5. J. Woodrow: Reactor Division, Harwell, Private communication.
6. G. Busz-Peuckert and W. Finkelnburg: *Z. Physik*, 1954, vol. 139, p. 212 (see also ref. 8).
7. W. Finkelnburg: "Symposium on high temperatures", 1956, p. 39, Stanford Research Institute, University of California (see also ref. 8).
8. D. R. Milner, G. R. Salter, and J. B. Wilkinson: *Brit. Welding J.*, 1960, vol. 7, p. 73 (this issue).
9. I. Amdur and E. A. Mason: "Physics of fluids", 1958, vol. 1, p. 370.
10. J. W. Mellor: "Comprehensive treatise on inorganic and theoretical chemistry", vol. 8, p. 366.
11. *Metal Industry*, 1954, vol. 84, p. 529; also C. Sheer and S. Korman: "Symposium on arcs in inert atmospheres and vacuum", 1956, London, Chapman and Hall, pp. 169, 184.
12. J. H. Moore and W. O. Dipietro: Electrochemical Soc., preprint, April 16th, 1953.

# METAL TRANSFER IN INERT-GAS SHIELDED-ARC WELDING

*By J. C. Needham, C. J. Cooksey and D. R. Milner*

*It is postulated that high-velocity plasma jets in the arc are responsible for metal transfer in high current density welding arcs. The proposed mechanism is that the plasma jet exerts a force on the globule as it forms on the end of the electrode wire, and when this force exceeds the restraining force of surface tension the globule begins to pull away from the electrode, the acceleration increasing as the area of the restraining neck decreases and thus exposing more of the globule to the jet. After the globule has become detached from the electrode it accelerates freely under the action of the jet to a terminal velocity which is determined by the force on the globule and the distance over which this force acts.*

*Experimental evidence for this hypothesis has been obtained from a high-speed cine-photography examination (9,000 frames per sec) of aluminium transfer, which showed that there was a force acting on the globule after it had become detached from the electrode and that the vapour emanating from the globule streamed in the direction of travel. Other subsidiary experiments have been carried out to demonstrate the presence of plasma jets in welding arcs.*

*A theoretical approach to the problem has been made by the application of the principles of fluid flow, and the free flight velocities and accelerations predicted show satisfactory agreement with experimental determinations. The conditions of removal of the drop are more difficult to formulate theoretically, but it has been shown that the plasma jet mechanism can account for the existence of the transition current and the marked change in drop diameter which is associated with it.*

## Introduction

THE mechanism of metal transfer is a problem which has long been outstanding in consumable-electrode welding. It is well known that forces exist in the arc which detach the molten droplets from the electrode and transfer them across the arc, and that these forces are greater than those due to gravity, so that overhead welding is possible. In inert-gas shielded-arc welding there is a characteristic transition current, below which this force is negligible, so that metal is transferred as large globules under gravity, whilst above the transition current the metal globules are much smaller and travel across the arc at high velocity.[1,2] The main hypotheses that have been advanced to explain metal transfer are based on the pinch effect[2,3] due to the constriction of the current in the wire electrode, and particularly in the neck of a globule falling from the end, and the expansion of gases in the metal at the electrode tip.[4] Neither of these hypotheses will explain all experimental observations and they have not been developed theoretically to a state that allows quantitative comparison to be made with experimental data. In the present work it will be shown, from a photographic study of droplet transfer, that it is not tenable that either of these mechanisms can account for the detachment and transfer of metal globules in inert-gas shielded welding, although the possibility that they exert a secondary influence cannot be ruled out. In the past, there have been two difficulties when investigating this problem: firstly, the basic knowledge of the physics of the arc and of the forces and processes which occur has been incomplete; and secondly, the metal-arc process is generally very complex, so that it is difficult to design experiments which isolate the individual parameters and thus allow unambiguous interpretation. Within the past decade these obstacles have been diminished, since the introduction of the inert-gas shielded-arc welding processes offer systems which are much more amenable to investigation, while the understanding of the behaviour and structure of the arc column has been advanced by the work of the Siemens group in Germany and of King[5] at the Electrical Research Association in Britain. In particular, Maecker[6] has demonstrated that plasma jets exist wherever an arc is constricted and that they attain high velocities, of the order of $10^4$ cm/sec. In the present work it is proposed that these jets are responsible for metal transfer.

As pointed out by Professor Rollason, in the introduction to this series of papers, metal transfer was being investigated independently at the Electrical

Manuscript received 30th November, 1959.
Mr. Needham is with the Electrical Research Association; Mr. Cooksey and Mr. Milner are in the Department of Industrial Metallurgy at Birmingham University. 

# MATERIAL TRANSFER CHARACTERISTICS

High Speed Photography of Pure Aluminium ($\frac{1}{16}$ in. dia.) in Argon

**Fig. 1—'Spray' Transfer and Arc Zone**

*Current 250 amp: Scale $2\frac{1}{2}\times$ full size: Exposure $10^{-5}$ sec each*

(*a*) Start of detachment with slight development of neck and some drawing out of droplet to less than wire diameter. Note bright bluish-purple central stream of about electrode diameter.

(*b*) Two droplets, one just above weld pool (transfer nearly completed) and the other in late stage of detachment showing severe neck formation. Note bright central stream as in (*a*) also envelops transferring droplet.

(*c*) Droplet in flight with small fragments (one near droplet and two further to right near weld pool) which come from break-up of neck at drop detachment and overtake droplet. Note that the bluish purple stream surrounding droplet is directed in advance towards the weld pool. This emanation, which is also shown by the fragments, is not the arc but is due to luminous metal vapour. The pale lilac jet at the electrode shows the start of a new vapour stream, but the arc proper (which is also just visible in (*a*) and (*b*) ) appears against the background illumination as a pale rounded cone varying in diameter from the electrode tip to the weld pool.

**Fig. 3—Sub-threshold Globular Transfer**

*Current 40 amp: Scale $\frac{1}{2}\times$ full size: Frame exposure $10^{-4}$ sec; interval $0{\cdot}3\times10^{-3}$ sec*

Transfer every 3 sec, mainly by gravity. Globule develops slowly, and supporting liquid neck remains constant (at about 90% of wire diameter) until globule weight exceeds the restraining forces due to surface tension and the neck rapidly collapses, as in the first four frames. At these low currents the arc plasma is pale blue with an orange tinted periphery, the anode zone appears to cover only the lower half of the pendant globule, and there are numerous independent cathode roots (white spots) on the plate. At globule detachment a bright, second, arc is formed between the wire tip and the globule, in series with the main arc. This condition lasts about $10^{-3}$ sec before the two arcs join up around the globule, which is falling slowly under gravity to the plate.

(The large globule actually bounces several times on the cold plate before coming to rest, the surface tension of the oxide skin containing the molten aluminium. The arc plasma freely envelops the transferring globule but the multiple cathode roots in general remain on the plate and do not play over the transferred globule, even though this would shorten the arc length.)

**Fig. 2—Simple and Compound Spray Transfer**

*Current 200 amp: Scale $3\times$ full size: Frame exposure $10^{-5}$ sec; interval $10^{-3}$ sec*

(*a*) **Transfer of single droplet**

Average time interval between main transfers is about $6\times10^{-3}$ sec. Frame 2 shows, compared with frame 1, some initial drawing out of the wire tip* and a slight indication of a neck which develops further in frames 3 and 4. The main transfer flight occurs in frames 5, 6 and 7 (a fragment from the neck is visible above the droplet in frames 5 and 6) with some subsequent oscillation of the new electrode tip after transfer (see frames 7, 8, and 9). Note also the development* of the bluish vapour stream, frames 1, 2, 3 and 4; its travel with the transferring droplet, frames 5 and 6; and, from frame 6 onwards, the start of the new vapour stream from the electrode. Although this stream varies considerably in diameter, the arc appears more constant, as shown by the pale greenish grey cone from the electrode tip to weld pool.

* *The lower sequence in* (b) *occurs immediately before the upper sequence* (a) *and hence shows the earlier stages in the melting of the electrode tip, frames* (b) 7, 8 *and* 9, *and the start of the vapour stream, frame* 9.

(*b*) **Multiple droplet transfer** (Subsidiary transfers from fluid wire tip)

Transfer of first droplet (frames 1, 2 and 3 with fragment from neck appearing above droplet, frame 2) leaves a sufficiently fluid wire tip, frames 2 and 3, for further subsidiary transfers: Firstly, a small pendant particle with a long drawn-out neck, frame 3, with its transfer nearly complete in frame 4; and secondly, the rest of the fluid tip which is transferred in frames 4 and 5. Note also the wire tip is again drawn out in frame 5 and leads to a small droplet transfer, frames 6, 7, 8 and 9. As previously, the vapour stream develops at the electrode tip and travels with the droplets. (See frames 1, 2, 3; 3, 4; 3, 4, 5; and 5 onwards, for each of the four transfers respectively.)

**Fig. 4—Normal Spray Transfer** (Effect of current on droplet size and velocity)

*Current 130–270 amp: Scale full size: Frame exposure $10^{-4}$ sec; interval $0{\cdot}3\times10^{-3}$ sec*

(*a*) 130 amp: Approximate minimum current for spray transfer. Transfer frequency 20/sec; Burn-off rate 120 in./min. Frames 1 and 2 show last stages of detachment (before transfer the molten wire tip is appreciably larger than the wire diameter) with a long drawn filamentary neck in frame 2, which becomes the fragment just visible at the top of the droplet in frame 3. The time of free flight is approximately $10^{-2}$ sec. Note the distortion and oscillation of the new wire tip immediately after detachment and, as previously, the movement of the vapour stream with the droplet. The arc appears pale white against the yellow/green background illumination.

(*b*) 170 amp: Transfer frequency 100/sec; Burn-off rate 150 in./min. The neck rapidly collapses in the first 3 frames and forms the fragmentary particle seen just above droplet in frame 4. The droplets are smaller and transfer more rapid than for (*a*) above (flight completed $10^{-3}$ sec after end of sequence shown) but other features, including some distortion of the wire tip immediately after transfer, are as previously described. The transfer velocity is given by the slope of the flight path, and the slight curvature of this path indicates acceleration in flight.

(*c*) 270 amp: Transfer frequency 300/sec; Burn-off rate 250 in./min. The neck rapidly attenuates to a thin filament (frame 3) and forms into a distinct fragment, frame 4. Again the droplets are smaller and transfer more rapid than for (*b*). The flight path shows curvature due to acceleration in flight, and superposed on this is the oscillation or deformation of the droplet during transfer. Note, in frames 6 and 7, the beginning of the neck and the drawing out of the wire tip for the next transfer, which just reaches detachment on the last frame. This sequence thus shows in frames 4–9 and 1–12 the typical complete cycle from one transfer to the next.

(a) (b) (c)

Fig. 1

(a)

Fig. 2

(b)

1 2 3 4 5 6 7 8 9

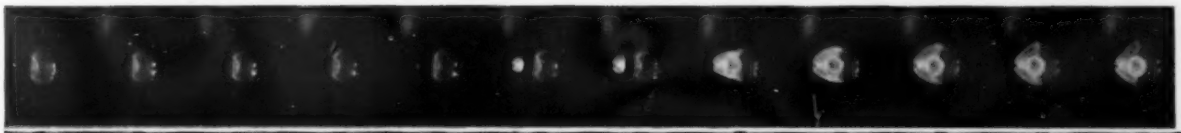
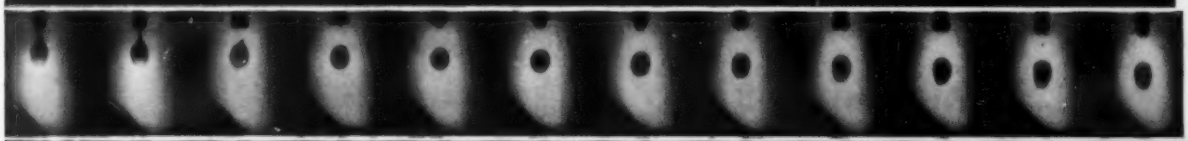
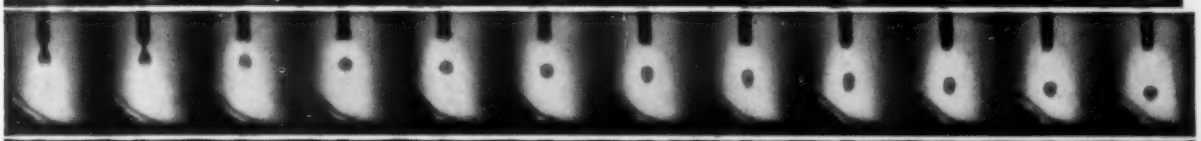


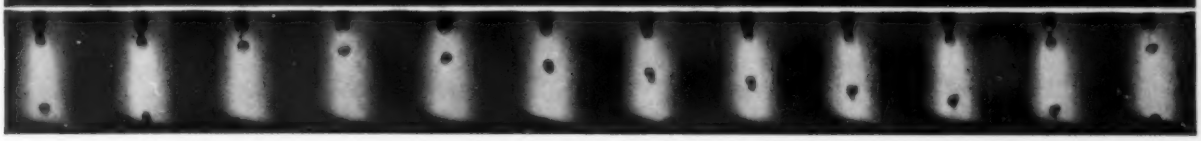
Fig. 3



(a)



(b) Fig. 4



(c)

1 2 3 4 5 6 7 8 9 10 11 12

# MATERIAL TRANSFER CHARACTERISTICS

High Speed Photography of Pure Aluminium ($\frac{1}{16}$ in. dia.) in Argon

**Fig. 1 'Spray' Transfer and Arc Zone**

*Current 250 amp: Scale 2½ × full size: Exposure $10^{-3}$ sec each*

(*a*) Start of detachment with slight development of neck and some drawing out of droplet to less than wire diameter. Note bright bluish-purple central stream of about electrode diameter.

(*b*) Two droplets, one just above weld pool (transfer nearly completed) and the other in late stage of detachment showing severe neck formation. Note bright central stream as in (*a*) also envelops transferring droplet.

(*c*) Droplet in flight with small fragments (one near droplet and two further to right near weld pool) which come from break-up of neck at drop detachment and overtake droplet. Note that the bluish purple stream surrounding droplet is directed in advance towards the weld pool. This emanation, which is also shown by the fragments, is not the arc but is due to luminous metal vapour. The pale lilac jet at the electrode shows the start of a new vapour stream, but the arc proper (which is also just visible in (*a*) and (*b*) ) appears against the background illumination as a pale rounded cone varying in diameter from the electrode tip to the weld pool.

**Fig. 2 Simple and Compound Spray Transfer**

*Current 200 amp: Scale 3 × full size: Frame exposure $10^{-3}$ sec: interval $10^{-3}$ sec*

(*a*) **Transfer of single droplet**

Average time interval between main transfers is about $6 \times 10^{-3}$ sec. Frame 2 shows, compared with frame 1, some initial drawing out of the wire tip* and a slight indication of a neck which develops further in frames 3 and 4. The main transfer flight occurs in frames 5, 6 and 7 (a fragment from the neck is visible above the droplet in frames 5 and 6) with some subsequent oscillation of the new electrode tip after transfer (see frames 7, 8, and 9). Note also the development* of the bluish vapour stream, frames 1, 2, 3 and 4; its travel with the transferring droplet, frames 5 and 6; and, from frame 6 onwards, the start of the new vapour stream from the electrode. Although this stream varies considerably in diameter, the arc appears more constant, as shown by the pale greenish grey cone from the electrode tip to weld pool.

* *The lower sequence in* (b) *occurs immediately before the upper sequence* (a) *and hence shows the earlier stages in the melting of the electrode tip, frames* (b) 7, 8 *and* 9, *and the start of the vapour stream, frame* 9.

(*b*) **Multiple droplet transfer** (Subsidiary transfers from fluid wire tip)

Transfer of first droplet (frames 1, 2 and 3 with fragment from neck appearing above droplet, frame 2) leaves a sufficiently fluid wire tip, frames 2 and 3, for further subsidiary transfers: Firstly, a small pendant particle with a long drawn-out neck, frame 3, with its transfer nearly complete in frame 4; and secondly, the rest of the fluid tip which is transferred in frames 4 and 5. Note also the wire tip is again drawn out in frame 5 and leads to a small droplet transfer, frames 6, 7, 8 and 9. As previously, the vapour stream develops at the electrode tip and travels with the droplets. (See frames 1, 2, 3; 3, 4; 3, 4, 5; and 5 onwards, for each of the four transfers respectively.)

**Fig. 3 Sub-threshold Globular Transfer**

*Current 40 amp: Scale ½ × full size: Frame exposure $10^{-3}$ sec: interval $0{\cdot}3 \times 10^{-3}$ sec*

Transfer every 3 sec, mainly by gravity. Globule develops slowly, and supporting liquid neck remains constant (at about 90% of wire diameter) until globule weight exceeds the restraining forces due to surface tension and the neck rapidly collapses, as in the first four frames. At these low currents the arc plasma is pale blue with an orange tinted periphery, the anode zone appears to cover only the lower half of the pendant globule, and there are numerous independent cathode roots (white spots) on the plate. At globule detachment a bright, second, arc is formed between the wire tip and the globule, in series with the main arc. This condition lasts about $10^{-3}$ sec before the two arcs join up around the globule, which is falling slowly under gravity to the plate.

(The large globule actually bounces several times on the cold plate before coming to rest, the surface tension of the oxide skin containing the molten aluminium. The arc plasma freely envelops the transferring globule but the multiple cathode roots in general remain on the plate and do not play over the transferred globule, even though this would shorten the arc length.)

**Fig. 4 Normal Spray Transfer** (Effect of current on droplet size and velocity)

*Current 130, 270 amp: Scale full size: Frame exposure $10^{-3}$ sec, interval $0{\cdot}3 \times 10^{-3}$ sec*

(*a*) 130 amp: Approximate minimum current for spray transfer. Transfer frequency 20/sec: Burn-off rate 120 in./min. Frames 1 and 2 show last stages of detachment (before transfer the molten wire tip is appreciably larger than the wire diameter) with a long drawn filamentary neck in frame 2, which becomes the fragment just visible at the top of the droplet in frame 3. The time of free flight is approximately $10^{-2}$ sec. Note the distortion and oscillation of the new wire tip immediately after detachment and, as previously, the movement of the vapour stream with the droplet. The arc appears pale white against the yellow green background illumination.

(*b*) 170 amp: Transfer frequency 100/sec: Burn-off rate 150 in./min. The neck rapidly collapses in the first 3 frames and forms the fragmentary particle seen just above droplet in frame 4. The droplets are smaller and transfer more rapid than for (*a*) above (flight completed $10^{-2}$ sec after end of sequence shown) but other features, including some distortion of the wire tip immediately after transfer, are as previously described. The transfer velocity is given by the slope of the flight path, and the slight curvature of this path indicates acceleration in flight.

(*c*) 270 amp: Transfer frequency 300/sec: Burn-off rate 250 in./min. The neck rapidly attenuates to a thin filament (frame 3) and forms into a distinct fragment, frame 4. Again the droplets are smaller and transfer more rapid than for (*b*). The flight path shows curvature due to acceleration in flight, and superposed on this is the oscillation or deformation of the droplet during transfer. Note, in frames 6 and 7, the beginning of the neck and the drawing out of the wire tip for the next transfer, which just reaches detachment on the last frame. This sequence thus shows in frames 4–9 and 1–12 the typical complete cycle from one transfer to the next.

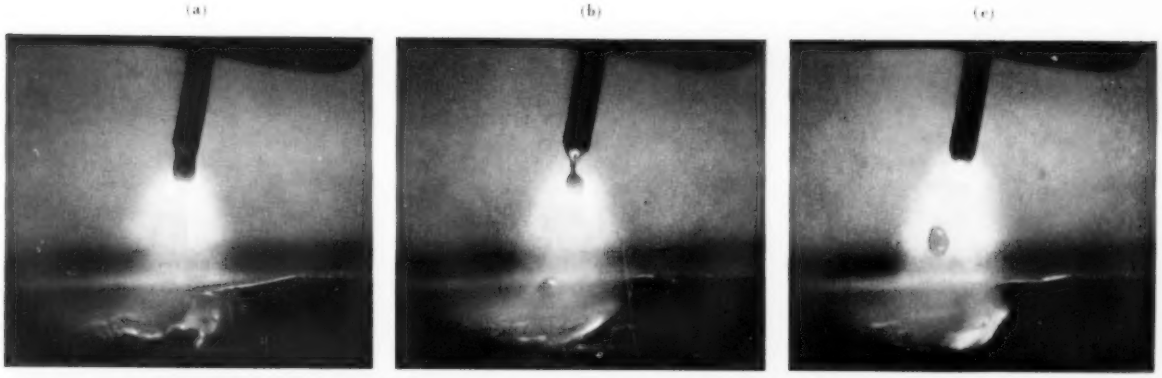



Fig. 1

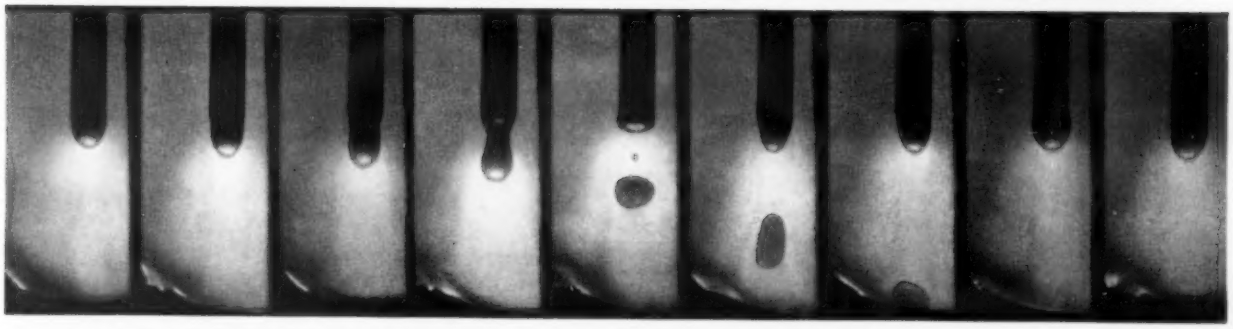



Fig. 2

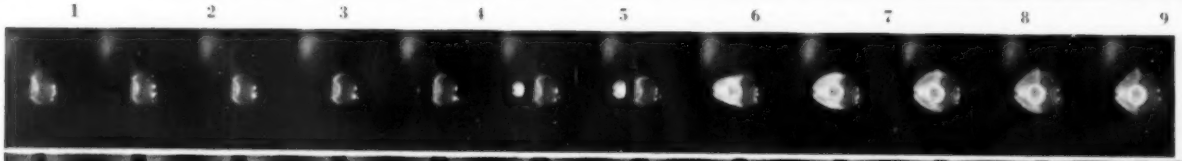


Fig. 3

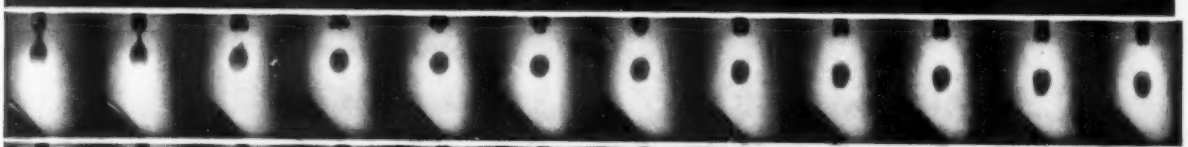
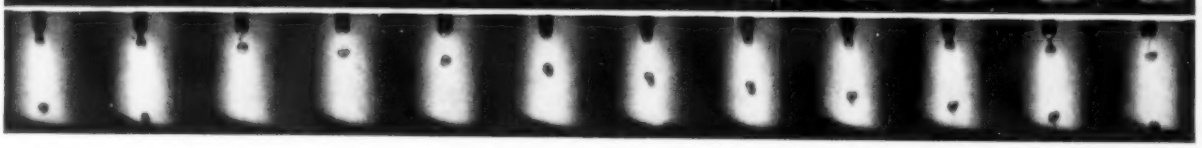


Fig. 4



Research Association and at the University of Birmingham. When this was realized, and it was found that both groups were of the opinion that plasma jets were responsible for the detachment and transfer of the droplets, the researches were co-ordinated into the co-operative effort reported in this paper. Two experimental approaches have been adopted. Firstly, the transfer of aluminium has been studied and analysed in detail by high-speed cine-photography (9000 frames per sec) to gain precise information about one system. In the second approach the relative behaviour of a number of metals, and the effect of changing polarity, on the terminal velocity and transition current, has been investigated to yield a broad framework of metal transfer characteristics. This work provides evidence for the hypothesis that plasma jets are responsible for metal transfer, while further support is available from a theoretical development of this concept. The theory, however, requires considerable further development and this in turn is dependent on a better knowledge of the interaction between the metal globules and the arc column.

## Experimental Techniques

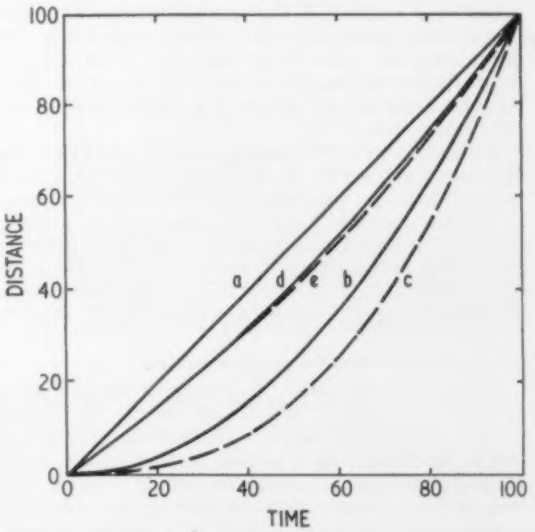
Two experimental approaches have been adopted to determine the characteristics of metal transfer. Various techniques of high-speed cine-photography were coupled to cathode-ray oscillography of arc voltage to determine details of metal transfer for $\frac{1}{16}$ in. dia. aluminium during bead runs with a self-adjusting arc. This method provided data on the size of the droplets and frequency of the transfer as a function of current, together with flight measurements from which particle velocity and acceleration were derived. On a broader basis, while the theory was developed by the application of the principles of fluid flow, the experimental work was extended to examine the change of terminal velocity of particles issuing through a hole in the plate, with current and with either polarity for a variety of electrode materials.

### High-speed cine-photography of metal transfer

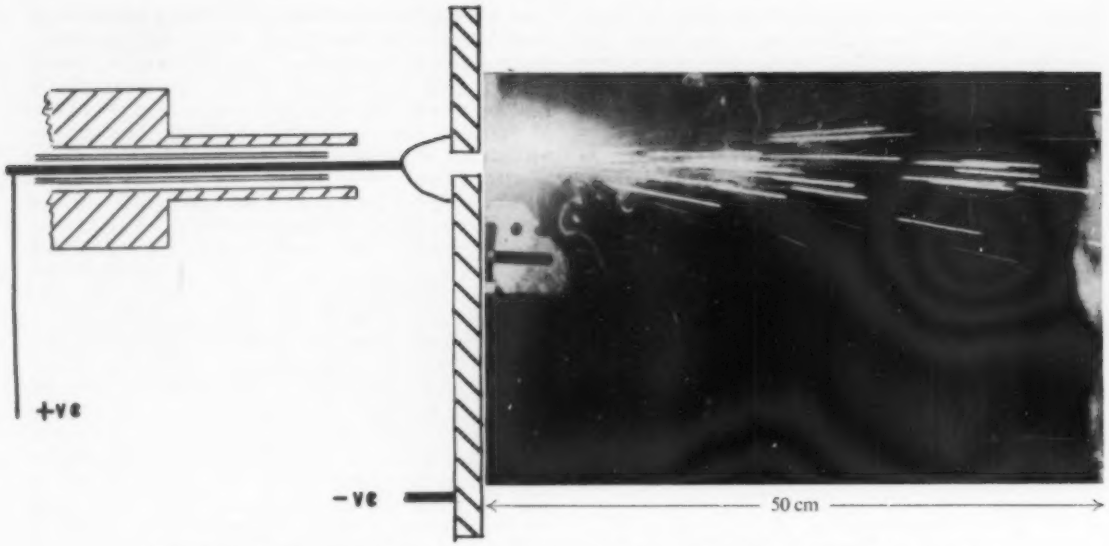
The experimental set-up for the bead runs has been described previously,[7] with a closely controlled welding machine and a low-voltage battery supply to give a high degree of self-adjustment. For measurement of particle size and velocity, high-speed cine films were taken at four current levels (135, 170, 220 and 270 amp corresponding to 120, 150, 200, 250 in./min wire feed rate) with comparatively long arcs (about 1 cm) to give an appreciable flight path. The electrode tip, crater, and transferring metal, were silhouetted by a high-intensity carbon arc (focussed on to the welding arc from behind), with the camera set at right angles to the traverse and using a long focus lens to give a near full size picture of the arc on the film. The maximum framing rate on the 16 mm camera used was 9000 pictures per sec, and the definition permitted flight measurement to $\pm$·002 in. (For Figs. 3 and 4, lower speed examples have been selected to show sufficient movement in the short sequences.)

However, even at the top framing rate, because the exposure was about half the frame time interval, the last stages of droplet detachment and collapse of the neck were not clearly defined. For this a special focal plane shutter was constructed, using a high-speed disc and a simple drum camera, to give larger (25×35 mm) pictures with an exposure of $10^{-5}$ sec (examples in Fig. 1) to record the details of the filamentary neck and its break-up into fragmentary particles. This camera was further modified to give a series of pictures with a narrow frame 10×25 mm, again with $10^{-5}$ sec exposure, but repeated at 1000 frames per sec (see examples in Fig. 2). Compared with the lengthy procedure required for the analysis of the high-speed cine films, these sequences, on the more compressed time scale, give rapid, broad estimates of velocity from the apparent slope of the droplet trajectory on the film.

Although the observed variable is distance against time, the fundamental parameter is the force acting on the drop, and in principle this can be derived from the slope of the velocity-time curve (*i.e.*, from the acceleration) for the droplet in free flight. However, in practice this requires an exceedingly accurate experimental determination of the distance/time curve, as can be seen from the various hypothetical flight paths for a free drop shown in Fig. 5. Considering first the case of a droplet in free flight with zero acceleration, the distance/time curve would be a straight line as (*a*), with a slope equal to the velocity. Alternatively, for zero initial velocity but with a constant acceleration the curve would appear as (*b*), or if there were a 10:1 increase of the acceleration with time the curve would appear as (*c*)—the difference between these curves is appreciable. However, the situation is considerably worsened by the fact that in travelling the distance required for detachment (about 3 mm out of the total arc length of 1 cm) the globule acquires about half its final velocity. The determination of the force acting on the droplet depends on the estimate of the acceleration, but with appreciable initial velocity the difference between a curve showing constant acceleration and one




5—*Distance/time curves for various hypothetical flight conditions:* (a) *Constant velocity;* (b) *zero initial velocity, but constant acceleration;* (c) *as* (b) *but changing acceleration;* (d) *and* (e) *as* (b) *and* (c) *respectively but initial velocity half final velocity*




*6—Diagram of arrangement for trajectory measurement of particle velocities, with a typical photograph of ejected particles (The scale is different on either side of the plate through which the particles travel, the photograph representing about 50 cm, whereas the line diagram covers about 5 cm)*

for a 10:1 variation is much reduced, as shown by curves (*d*) and (*e*) in Fig. 5. At their maximum separation there is only about 1% difference in these two curves, and hence great care is required in measurement for the derivation of acceleration.

Thus the determination of acceleration was given considerable attention and the method finally adopted to avoid experimental bias was to calculate, for the measured distance/time points of the droplet in the high-speed cine films, the best fitting (least squares) curve of the form $y=A+Bx+Cx^2+ \ldots$ by the polynomial methods.[8] The second order polynomial for the mean acceleration gave a curve with a standard deviation of the errors of less than 0·002 in. (which was the probable experimental error) and a rough estimate was also made of any change of acceleration from the third order term.

The frequency of the droplet transfer, and hence the mean drop volume (from the wire feed rate) for a wide range of currents, was determined from the arc voltage which was recorded by direct connection to a high-sensitivity P.D.A. cathode ray tube and drum camera. Sharp pips in the arc voltage trace were identified (by simultaneous c.r.o. records and high-speed films) with the detachment of droplets from the electrode wire.

#### Trajectory measurements of particle velocities

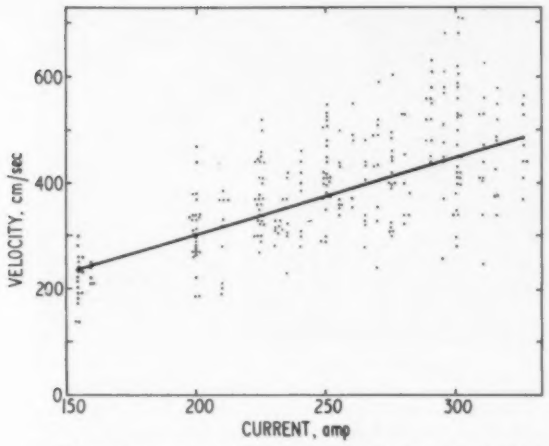
While the high-speed photographic method gives detailed information about the mode of droplet transfer, the terminal velocity which the droplets attain can be determined by a simpler method in which the metal globules pass through a hole or slit in a plate and their trajectories are recorded photographically by a conventional camera. The effect of a number of variables on the terminal velocity can be determined relatively rapidly by this method. Larson[4] used a similar technique to determine trajectories, and hence particle velocities in metal-arc welding, by making a vertical weld between two plates, which were arranged with an excessive joint gap so that a proportion of metal globules passed between the plates. In the present work a commercial consumable-electrode torch was fixed to project metal horizontally through a circular hole in a copper plate which acted in place of a work plate. It was found that a $\frac{3}{8}$ in. dia. hole in a $\frac{1}{8}$ in. thick plate would allow several runs of about 10 sec each to be made, whilst a more permanent system could be established by water cooling the plate. The issuing particles were photographed with an exposure of about 1/100 sec (the exact shutter speed being determined by photographing a hole in a disc rotating at known speed), and the velocity was determined from the horizontal component of the streaks on the trajectories. An example of the type of photograph obtained is shown in Fig. 6, in which the torch and plate, which would otherwise be obscured by arc glare are shown in diagrammatic form.

Using this technique the relationship between the terminal velocity and current has been determined for aluminium–5% silicon, copper, titanium, nickel, and mild steel for both positive and negative polarity.

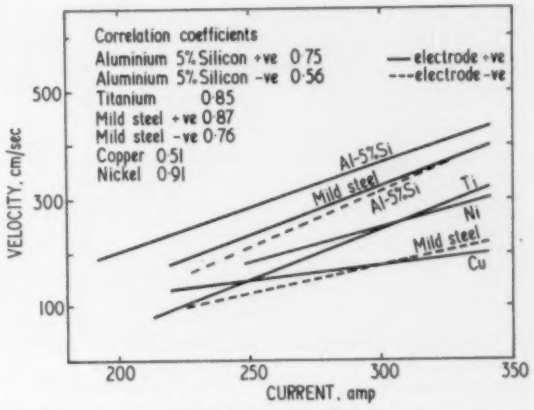
## Results

#### Variation of particle velocity with current

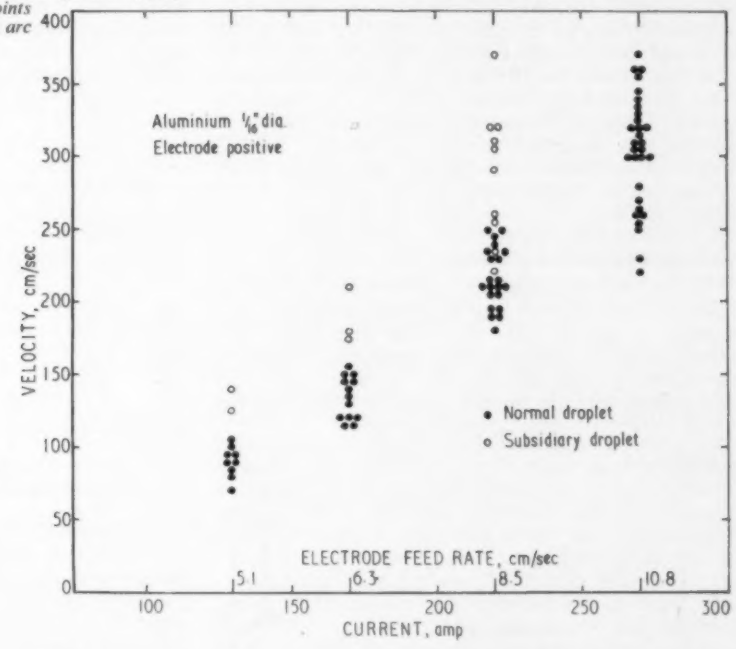
The determination of the terminal velocity of particles issuing from a hole, by recording their trajectories, showed that with fixed wire speed, current, and mean arc length there was a considerable scatter in the measured velocity of the particles. This is illustrated (Fig. 7) by the results of a large number of velocity determinations for Al–5% Si with an arc length of 1 cm, and for this it is convenient to represent the trend of the velocity/current relationship by the




7—*Effect of current on individual particle velocities for Al–5% Si, with the regression line through these points (c.f. Fig. 9). (Electrode positive and an arc length of 1 cm—trajectory method)*




8—*Regression lines relating particle velocity to current for a range of metals. Arc length 0·5 cm*




9—*Effect of current on individual particle velocities for aluminium. (Data by high-speed cine-photography)*

regression line. The threshold or transition current is represented by the point at which the curve begins (about ±5 amp) and for this case represents the minimum current at which particles were projected through the hole.

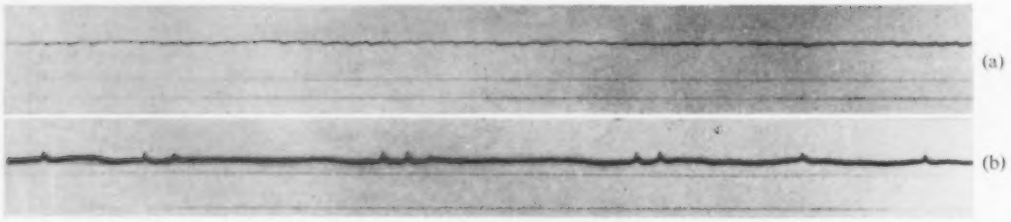
The relative velocities acquired by Al–5% Si, nickel, mild steel, titanium, and copper with an arc length of 0·5 cm are shown by the set of regression lines in Fig. 8, which were derived as for the Al–5% Si. With negative polarity it was found that for nickel and copper spray transfer could be obtained only with the electrode burning off inside the hole, and the terminal velocity was then about 300 cm/sec. The values of the transition current determined in these experiments are summarized in Table I.

The scatter in the droplet velocities is also shown in the high-speed film results for the bead run tests, Fig. 9, even when, with the degree of control possible, the current fluctuation is less than ±1% and a succession of droplets are taken over a short time. At the highest current investigated, 270 amp, the transfer frequency was fairly regular (see oscillogram Fig. 10*a*),

**Table I**

**Experimentally determined transition currents for various metals**

| *Metal* | *Transition Current* | |
|---|---|---|
| | *Electrode Positive* | *Electrode Negative* |
| Al–5% Si | 125 | 235 |
| Titanium | 215 | 295 |
| Copper | 220 | 275 |
| Mild Steel | 220 | 240 |
| Nickel | 250 | 250 |




10—*Oscillogram of arc voltage:* (a) *At 270 amp, regular transfer frequency 300/sec;* (b) *at 170 amp, irregular transfer showing 'double' and 'treble' transfers. (Time—0·01 sec/cm)*

but at the lower currents distinct grouping into 'double' or even 'treble' transfers occurred as well as the single transfers (Fig. 10*b*). The compound transfers are due to excess fluid at the electrode tip after one transfer, leading to a subsidiary droplet which is usually smaller than average (Fig. 2*b*). These secondary transfers (shown separately in Fig. 9) had an appreciably higher average velocity and add to the apparent scatter in velocities at a given current.

A comparison at 270 amp of the final and initial (*i.e.*, just after detachment) free flight velocities is shown in Fig. 11. The average velocities were 300 and 180 cm/sec respectively, and the average overall acceleration (from $v^2 - u^2 = 2as$) is thus about 40,000 cm/sec per sec (about 40 times gravity) for a 7 mm flight.

#### Variation of droplet size with current

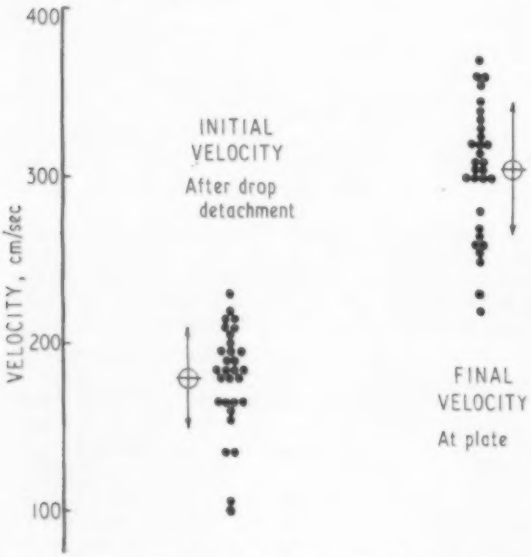
With a self-adjusting arc, as the wire feed rate is reduced, the current drops correspondingly. The transfer frequency also falls, but somewhat more rapidly than the current, so that there is an increase in the mean droplet size. At the transition point for aluminium, with no further change in feed rate, the system changes completely to the sub-threshold state with large globules transferring very infrequently but with a further decrease in the current of about 40 amp.

Even allowing for the discontinuity in the current/burn-off-rate relationship at the transition point, there is still a large change in the transfer size with current around this region. Table II shows typical transfer frequencies and calculated diameters of a spherical drop of equivalent volume for equal increments of current and covering the range from sub-threshold to normal spray transfer for aluminium.

**Table II**

**Transfer frequency and size with current for aluminium $\frac{1}{16}$ in. dia.[7]**

| *Current, amp* | *Burn-off Rate, in./min* | *Transfer Frequency per sec* | *Dia. of Equivalent Sphere, cm* |
|---|---|---|---|
| 20 | 25 | 0·15 | 0·61 |
| 60 | 70 | 0·6 | 0·58 |
| 100 | 120 | 2 | 0·46 |
| 140 | 120 | 30 | 0·18 |
| 180 | 160 | 90 | 0·15 |
| 220 | 200 | 200 | 0·12 |




11—*Comparison of initial and final velocities for aluminium, 270 amp*

## Interpretation of Experimental Results

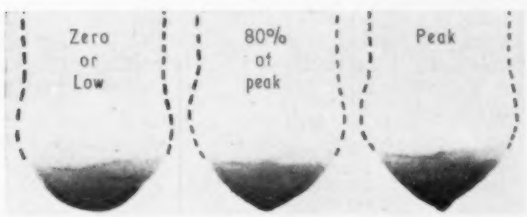
#### Plasma jet hypothesis

It was pointed out in the Introduction that the two main hypotheses previously advanced to account for the high-velocity metal transfer propose that it arises either from the pinch effect on the electrode, or from the expansion of gases contained in the electrode material. High-speed cine-photography shows, however, that neither of these hypotheses is sufficient for spray transfer in inert-gas-shielded welding. The former because there is a force on the globule after it has become completely detached from the electrode, and thus when no current is carried by it; and the latter is not consistent with the regular type of well-directed transfer that takes place. Another mechanism must therefore be sought, and the authors propose that it is concerned with the existence of the plasma jets which form in arcs.

That the arc exerts a pressure tending to separate its electrodes is well known and has been demonstrated, for example, by experiments with a plate suspended on a torsion balance.[9] At low currents these forces are only a few dynes, but at high currents they can amount to some grams weight. The increasing concavity of a

(a) 12—*Photograph showing acceleration of quartz particles by plasma stream* (b)

weld pool with increasing current, which is evidence of this force, is well known, and in the extreme nearly all the molten metal is swept out of the crater.[7] These forces are particularly marked in consumable-electrode welding, but any suggestion as to their origin is complicated by the material transfer. However, similar effects are produced with tungsten inert-gas, carbon-arc, and other non-consumable electrode arcs, where the force between the electrode and plate must be communicated *via* the arc plasma. Maecker,[6] in 1955, showed that the origin of this force lay in the plasma jet, which has a velocity of the order of $10^4$ cm/sec, and is formed wherever an arc is constricted and there is a current density gradient. The plasma jets can originate from either or both electrodes, but with a small diameter electrode the welding arc is mainly constrained by the wire, and the main plasma stream operates from electrode to plate, irrespective of the polarity or electrode material. It is difficult to determine the detailed characteristics of plasma jets while metal transfer is also present, but evidence which is more relevant to the present problem was obtained from an experiment with a non-consumable-electrode argon arc (electrode negative and water-cooled copper plate) arranged horizontally, in which small quartz particles, 0·03 mm dia. were dropped near the tapered electrode. The particles were swept into the arc and were found to bounce off the plate at high speed. With a plate containing a $\frac{1}{4}$ in. hole, the particles passed through and travelled several feet. The existence of a plasma stream is also shown in Fig. 12, where the quartz is dropped past the plate hole on the opposite side of the arc. Figure 12*a* shows the small deflection of the falling particles due to the argon gas stream alone, but with a 150 amp argon arc the plasma jet issuing through the hole (Fig. 12*b*) causes the sharp cut off and imparts a high velocity to the particles. From high-speed cine-photography the peak accelerations are of the order of 100 *g* and the velocity about $10^3$ cm/sec. It should be noted that the particles are not electrically connected with the arc and are free from magnetic or electrostatic effects, and that the issuing gas velocity, even at a few centimetres from the plate hole, must be well in excess of $10^3$ cm/sec. Another phenomenon which may be associated with the gas flow over the electrode and into the arc is found with a.c. argon arcs at high currents when the tungsten tip is molten. During the period when the tungsten is negative a small pimple appears on the fluid electrode tip, and this grows and collapses with the current loop (Fig. 13). Even though the movement takes less than 1/100 sec, it is so reproducible that it can be visually observed with a simple stroboscope.




13—*Effect of a.c. current loop on shape of tungsten tip*

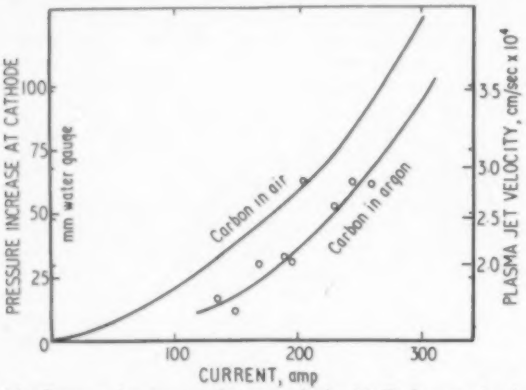
In consumable-electrode welding, evidence for the plasma jet is shown by the behaviour of the metal vapour stream (Figs. 1 and 2). If the droplets were ejected by some mechanism from the electrode the metal vapour would stream behind the droplet, like a comet's tail. However, both for the fragmentary particles and the main droplet, even when the latter is appreciably off axis, this stream is directed forward in advance of the transferring metal. But the strongest evidence is provided by high-speed photography of the transferring particles in consumable-electrode arcs, which show appreciable acceleration in flight. For example, with $\frac{1}{16}$ in. dia. aluminium the transfers show a mean free flight acceleration of the order of 40,000 cm/sec per sec at 270 amp.

As already stated the plasma jet arises primarily from the wire-to-plate geometry, since the current is constricted at the wire electrode by reason of its small diameter, while the arc broadens considerably towards the plate to be welded. This is consistent with the experimental observation that the phenomenon of metal transfer will occur with electrode both positive and negative, but superimposed on this is the influence of the cathode and anode current densities of the electrode materials, which determine the detailed characteristics of metal transfer. Unfortunately it has not yet been found possible to determine the extent and velocity of the plasma jet in consumable-electrode welding. However, Maecker[6] was able to make several measurements of the characteristics of the plasma jet in the non-consumable carbon arc in air, and in

particular, he was able to measure the pressure increase at the cathode, which can be related to the forward velocity to give a mean plasma-velocity/current relationship. Maecker was able to show theoretically that the velocity $v$ of the plasma jet is related to the current $I$, current density $j$, and the pressure increase $\Delta p$, at the constriction by:

$$v^2 \propto Ij \propto \Delta p \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

King[5] has shown that arcs in dissociable gases operate with a higher current density than in monatomic gases, so that the pressure increase, and hence the plasma jet velocity, which Maecker found for the carbon arc, would be expected to be higher than that for the argon arc. Measurements were therefore made of the pressure increase at a carbon cathode, but with the arc operating in argon, with a 1 mm hole drilled down the centre of the carbon cathode connected to a manometer. The pressure increase was converted to a mean forward velocity by the equation $p = 1/2\rho v^2$, where the density of argon at the cathode was taken as $1{\cdot}8 \times 10^{-5}$ g/cu.cm corresponding to the temperature of 30,000°K. found by Busz-Peuckert and Finkelnburg[12] for the column of the argon arc, immediately in front of the cathode. The pressures and associated velocities are shown in Fig. 14. More experimental scatter of results was found than reported by Maecker,




14—*Pressure increase at the arc cathode:* (a) *Carbon arc in air, (Maecker);* (b) *carbon arc in argon*

and in addition no satisfactory measurements could be made at currents less than 135 amp, owing to the tendency of the arc to operate from a point to the side of the hole in the cathode. Unfortunately it was not possible to carry out similar measurements with the carbon rod as the anode, the more generally used polarity in consumable-electrode welding, for excessive heating caused the carbon to burn away too rapidly. Despite the unsatisfactory nature of these results, in the absence of other information it is necessary to use the plasma jet velocities derived from them, and so a curve has been drawn through the experimental points, parallel to Maecker's curve, to provide the required jet-velocity/current relationship. These velocities can be expected to be of the same order as those occurring in consumable-electrode welding arcs but should correspond more closely to electrode negative arcs with an electrode diameter which gives the same cathode current density as that occurring in the carbon arc.

In the following section the detailed mechanism by which the plasma jet exerts a force on the droplet will be considered, but the feasibility of the mechanism can be seen from a comparison of the force required to produce the observed acceleration of the droplet, with that available in the jet. The data for transfer at 270 amp showed an acceleration of 40,000 cm/sec per sec, with a mean droplet size of 0·12 cm dia. (weight 2·5 mg), so that the accelerating force required is about 100 dynes. The force associated with the pinch effect acting on the gas for a changing section of diameters $d$ and $d'$ amounts to a total axial component given by:[3]

$$f = I^2 \cdot \log_e \frac{d'}{d} \times 10^{-2} \text{ dynes}$$

Assuming the larger diameter is given by the weld pool size (about 1 cm dia.) then for a current of 270 amp on a $\frac{1}{16}$ in. dia. electrode this is $10^3$ dynes and acts from the smaller section to the larger. Maecker measured this force for the carbon arc in air by determining the back reaction force on the electrode and found a similar value.

**Quantitative development of plasma jet hypothesis**

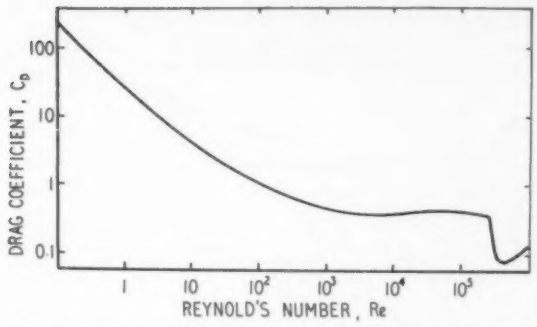
In the previous section it has been shown that the plasma jet mechanism of metal transfer is feasible, and it is now proposed to attempt a quantitative development of this hypothesis. The postulated mechanism is that the high-velocity plasma jet exerts a force on the molten globule as it forms on the end of the electrode, and when this force exceeds the restraining force of surface tension the globule begins to pull away from the electrode, the acceleration increasing as the area of the restraining neck decreases, exposing more of the globule to the plasma jet. After the globule has become detached from the electrode it accelerates freely under the action of the plasma jet to a terminal velocity governed by the force on the globule and the distance over which this force acts. It will be assumed that the velocity of the jet is that derived from the measurements of the pressure increase at a carbon electrode, presented in Fig. 14. It then becomes necessary to equate the jet velocity to the force acting on the globule. This problem is most amenable, when a round globule forms on the end of the melting electrode and then becomes detached and is of spherical form as it travels across the arc. The photographs reproduced in Figs. 1–4 show that for aluminium this is a reasonable assumption for the current range (up to 270 amp) considered in the present work.

*Acceleration of globule in free flight*

Since the conditions of detachment of the drop are rather complex, the free flight of the drop will be considered first. The force $D$ which is exerted on a sphere placed in a high-velocity stream of fluid, has been the object of a number of investigations (see for example, Schlichting[11]), the results of which have been expressed as a relationship between two non-dimensional groups, *i.e.*:

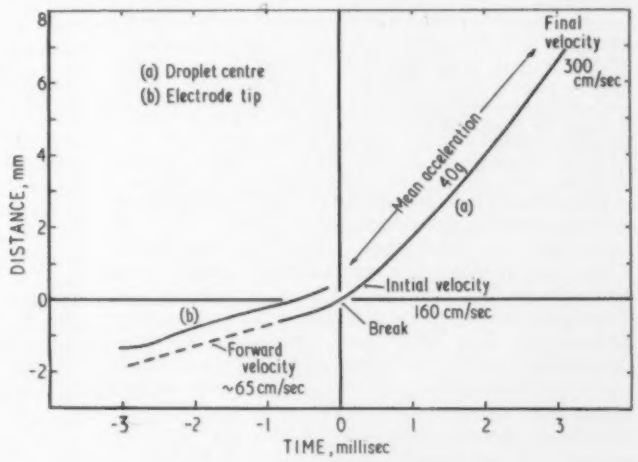
$$\frac{D}{\pi/8\ v^2\rho d^2} = f\frac{(v\rho d)}{\eta} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where $d$ is the diameter of the sphere.
$\eta$ is the gas viscosity
$v$ is the gas velocity
and $\rho$ is the gas density.



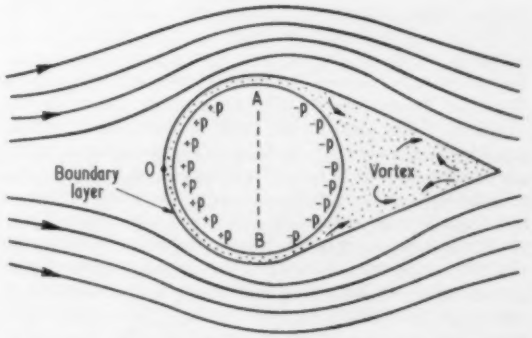

15—*Relationship between the drag coefficient* $C_D$, *and Reynold's number* Re (*from which the force exerted on a sphere by the gas stream can be derived*)

The first dimensionless group is known as the drag coefficient $C_D$ while the second is Reynold's number $Re$, and the relationship between the two is reproduced in Fig. 15. It is thus possible to calculate the acceleration of a globule of known size as it traverses the arc, if the velocity, density, and viscosity of the gas stream are known, and this will be attempted for the conditions corresponding to metal transfer to a plate at 270 amp with an arc length of about 1 cm for which experimental data is shown in Fig. 16. Before this can be done it is necessary to consider the values that are to be ascribed to the parameters in equation (2).




16—*Typical distance/time curve for droplet. (Aluminium, 270 amp with break at origin of axes*

The forward velocity of a free plasma jet decreases with the distance from the point of constriction, as shown by the flow characteristics of the plasma jet in a 200-amp carbon arc determined by Wienecke,[12] and this effect is further accentuated by the presence of the weld plate, which diverts the jet sideways. However, for the purposes of the present calculation the velocity determined from the pressure increase at the cathode will be used, bearing in mind that this overestimates the force exerted by the jet on the globule. The velocity $v$ of the gas stream relative to the globule decreases as the globule gathers speed, but this effect is negligible, for the gas stream has a velocity of the order of $10^4$–$10^5$ cm/sec, whereas the drop velocity only attains $10^2$–$10^3$ cm/sec during the first centimetre of travel. There is now the problem of assigning values to the density and viscosity, both of which are markedly dependent on the temperature. In the column of the high-current argon arc the temperature varies from 30,000°K. just in front of the cathode, to around 5,000°K. at the periphery of the arc,[10] while at the surface of the globule the temperature must be between the melting and boiling points, with a gaseous boundary layer at the surface of the sphere which has a mean temperature between that of the column and that of the globule. It is therefore necessary to decide the origin of the force exerted by the plasma jet, so as to decide which is the relevant temperature. For the conditions of gas flow in the present problem (*i.e.*, Reynold's numbers of the order of 10 to $10^2$), a gas stream exerts a force on a sphere placed in its path by pressure drag and skin friction[11] as shown in Fig. 17. The pressure drag results from the momentum of the gas stream being transformed into a pressure increase in front of the body, and a vortex motion at the rear which creates a decrease in pressure. The pressure increase in front of the sphere originates in fluid flow at a distance from the body for which the high temperature of the column is relevant. The vortex motion is initiated by the conditions in the boundary, but takes place at a distance from the sphere so that




17—*Diagrammatic representation of sphere in gas stream, showing the way in which gas exerts a force on the sphere*

boundary layer and bulk plasma temperatures are involved. Skin friction is the result of the marked velocity gradient over the boundary layer adjacent to the body, for which the temperature of the boundary layer, which is closer to the temperature of the globule, should be taken. Thus a highly refined analysis of the processes which make up the total force, and their dependence on temperature, is required to calculate the total force accurately. Unfortunately this analysis cannot as yet be carried out.

To some extent the changes in density and viscosity with temperature cancel each other. Thus, using the values for the viscosity of argon derived by Amdur and Mason[13] for temperatures up to 15,000°K., and using the ideal gas law, which should be adequate, for the determination of density values, the force $D$ does not vary greatly between 5,000° and 15,000°K. (Table III). Since the temperature varies between about 30,000°K. in the arc column and about 2,000°K. at the surface of the metal globule, the intermediate value of 15,000°K. will be used in the calculations that follow, with the corresponding values of viscosity and density.

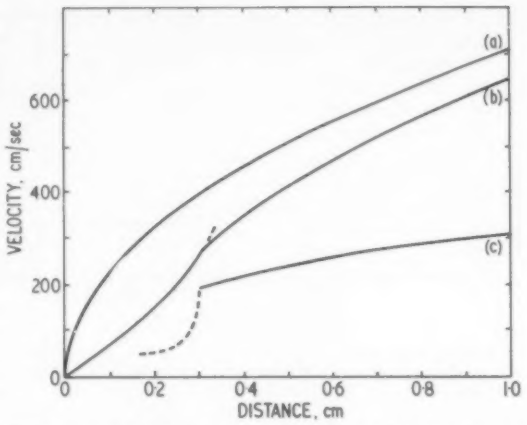
**Table III**

**Variation of force exerted by plasma jet with temperature**

| *Temperature, °K.* | *Density, g/cu.cm × 10⁻⁵* | *Viscosity,* poises × 10⁻³* | *Force,† dynes* |
|---|---|---|---|
| 5,000 | 10·7 | 1·83 | 740 |
| 10,000 | 5·33 | 3·1 | 600 |
| 15,000 | 3·56 | 4·2 | 630 |

* Values for $\eta$ from ref. 13.
† Calculated for 0·2 cm dia. sphere.

It is now possible to calculate a theoretical particle-velocity/distance relationship to compare with the experimentally determined curve for transfer at 270 amp (for which the mean particle diameter was found to be 0·12 cm), using the value of plasma jet velocity derived from the pressure increase at a carbon cathode, *i.e.*, $2{\cdot}9 \times 10^4$ cm/sec. The result is shown by curve (*a*) in Fig. 18, which should be compared with the experimental result of curve (*c*). The experimental curve only records the free flight of the drop after the neck fractures, *i.e.*, from 3 to 10 mm, and over this distance the theoretically predicted rate of increase of velocity is over twice the experimentally determined value. In the first 3 mm of travel the acceleration of the drop is less than the free flight value because it is still attached to the electrode by a restraining liquid neck. In addition, the size of the drop decreases as it becomes detached from the end of the electrode owing to the division of the liquid in the neck between the electrode and the drop (*see* Figs. 1–4), and a larger drop accelerates more slowly. An estimate has been made of the effect of these factors by assuming that the radius of the liquid neck decreases linearly from that of the electrode wire to zero in 3 mm, and that in the same distance the drop diameter varies linearly between just greater than the wire diameter prior to detachment to the experimentally observed value of 1·2 mm when free. The result is given by curve (*b*) Fig. 18, which shows the sum of these two effects to make only a small change in the velocity as expected for a fixed




18—*Variation of globule velocity with distance for aluminium at 270 amp:* (a) *Calculated for 0·12 cm dia. droplet*; (b) *calculated as* (a) *but allowing for restraint of neck*; (c) *experimental data*

total distance of 1 cm. These final velocities are still of the order of twice the experimental value.

*Detachment of drop from end of electrode*

The conditions governing the detachment of the drop are more complex, and it is possible to estimate only very roughly the force exerted by the plasma jet on the globule, as it forms on the end of the electrode, from the force acting on a free sphere. In addition, the force exerted by gravity can play an appreciable part, but this will be considered later. As mentioned previously the total force on a sphere consists of two parts, skin friction and pressure drag. There is a pressure increase at the front of the sphere which is a maximum at the stagnation point $O$, Fig. 17, and decreases to zero at the equator $AB$, while the skin friction as a function of the frontal area is a minimum at the centre and a maximum at the equator. At the rear of the sphere the vortex motion results in an approximately uniform depression. For the range of Reynold's numbers with which the present work is concerned these forces are of the same order of magnitude, and so in the absence of more detailed information, it will be assumed that the front and rear projected areas of the sphere contribute equally and uniformly to the total force. Then, for the case where the electrode end melts and assumes an approximately hemispherical shape, half the total force acts to detach it. If the diameter of the globule exceeds that of the electrode, so that it projects into the gas stream, the force acting on it is given approximately by:— $\frac{1}{2}D\,(1+(R^2-r^2)/R^2)$, where $R$ is the radius of the globule, and $r$ the radius of the electrode wire. The globule begins to detach from the electrode when this force exceeds the restraining force of surface tension, *i.e.* when

$$\tfrac{1}{2}D\,(1+(R^2-r^2)/R^2) = 2\pi r\gamma \quad \ldots\ldots\ldots\ldots \quad (3)$$

where $\gamma$ is the surface tension of the electrode material.

The need to know the surface tension was eliminated by an experimental determination of the mass of the drop which formed on the electrode at very low currents and fell freely under gravity ($2\pi r\gamma = mg$,

where $m$ is the mass of the drop and $g$ the acceleration due to gravity). The results of the determination of the surface tension of mild steel, nickel, copper, titanium and Al–5% Si by this method are presented in the second column of Table IV.

**Table IV**

**Surface tension and restraining forces of various metals**

| *Metal* | *Surface Tension,* dynes/cm* | *Restraining Force, dynes* |
|---|---|---|
| Al–5% Si | 605 | 302 |
| Titanium | 1220 | 608 |
| Copper | 895 | 446 |
| Mild Steel | 1240 | 618 |
| Nickel | 1390 | 693 |

* Values calculated from maximum globule weight at low currents, without allowance for neck.

To illustrate the magnitude of the forces involved the situation is considered where a globule on the electrode end has a diameter equal to twice that of the electrode wire. Table IV shows the magnitude of the restraining force of surface tension for the metals investigated, while the force exerted by the plasma jet, calculated from the determination of the pressure increase at a carbon cathode, varies from 165 dynes at 150 amp to 820 dynes at 350 amp. The force exerted by the jet is thus comparable with the restraining force.

*Variation of particle size and transition current*

An understanding of the transition from globular to spray transfer, and of the decrease in particle size with current, requires a more detailed analysis. Two cases arise, the first where metal transfer is taking place horizontally, so that the force exerted by gravity on the drop plays no part in its forward propulsion. The second case is transfer vertically downwards, where both gravity and the plasma jet act to detach the drop. In the former case, for a given current, as the end of the electrode melts the globule grows in diameter and, if the velocity of the plasma jet were to remain constant, the force exerted on the globule would increase as its size increased, until it was sufficient to overcome the restraining force of surface tension; the globule would then be detached by the action of the plasma jet at the size of globule given by equation (3). With decrease in current the velocity and therefore force per unit area exerted by the plasma jet decreases, while the restraining force remains constant. Therefore the globule size must increase before detachment takes place. (Eventually, if the current is lowered sufficiently, the force exerted on the drop by gravity is greater than that exerted by the plasma jet.) However, as the globule increases in size it also presents a larger current carrying area at the electrode, so that the constricting effect, and hence the velocity and force of the plasma jet is less at any particular current than it is for an arc constricted to the wire diameter. This is a co-operative phenomenon, since the more the size of the globule increases the weaker the plasma jet becomes, so that over a relatively small current range there is a marked change in the size of globule transferred.

To deal quantitatively with this problem, and to obtain the diameter of the drop detached at any particular current, a reduced velocity must be used to calculate the force $D$ in equation (3), and this can be obtained from Maecker's velocity relationship (equation 1). If the velocity of the plasma jet with the current passing through the wire, radius $r$, is $v_0$, and a drop radius $R$ develops on the end of the electrode, then from equation (1) assuming the gas density remains constant with current, the reduced velocity $v_1$ is given by:

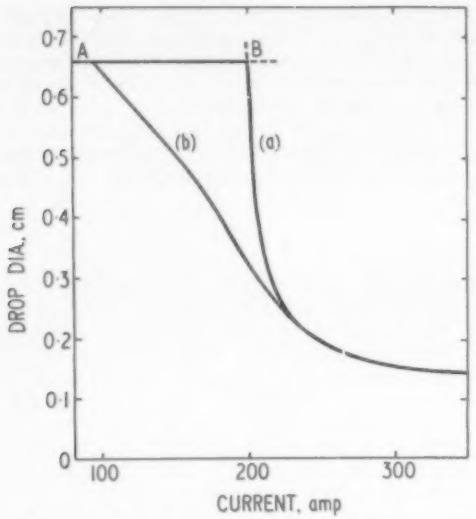
$$v_1 = \frac{v_0 r}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Inserting this reduced velocity in equations (2) and (3), and carrying the calculation through for aluminium, the variation of drop diameter with current shown by curve (*a*) in Fig. 19*a* is obtained, in which there is a very marked change in the drop diameter over a range of 10–20 amp. The drop will never have a larger diameter than that given by the line $AB$, however, since this represents the size of drop which is detached by gravity ($2\pi r\gamma = mg$). On the basis of this argument the transition current is therefore approximately given by that current at which the force of gravity equals the force exerted by the plasma jet. However, in view of the divergence between the theoretically calculated and experimentally determined force acting on a free drop, and the further approximations that have had to be made to obtain the conditions of detachment of the drop, it cannot be expected that the theoretical values of the transition current would have a worthwhile significance, although the value of 200 amp for aluminium compares favourably with the corresponding experimental value of 235 amp for consumable-electrode negative current connection. According to the foregoing simplified theory, the variation of the transition current from one metal to another is dependent only on the surface tension; thus, although the transition currents might not be exact it might be expected that the theory would place the metals investigated in the correct relative order. A comparison of the surface tensions presented in Table IV, and of the transition currents in Table I, shows that although there is a rough correlation the agreement is far from complete, and furthermore varies with polarity. This means that the relative behaviour of a group of metals cannot be derived on the assumption that the plasma jet action and geometry of drop removal is identical in all cases, and it is therefore necessary to take account of individual metal characteristics to obtain a complete account of metal transfer.

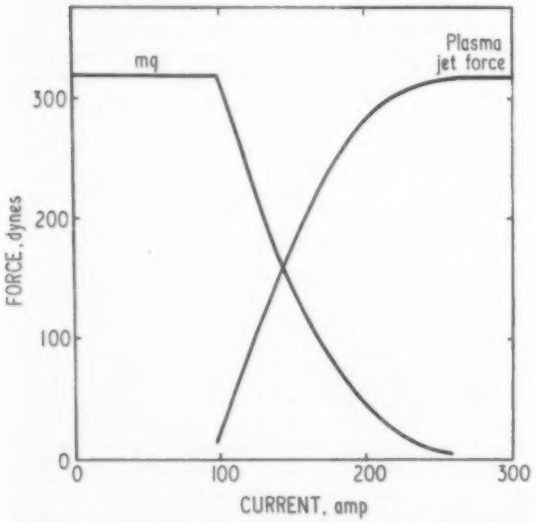
When metal transfer takes place in a vertically downwards direction the force exerted by gravity on the drop also acts to detach it, so that equation (3) becomes:

$$\tfrac{1}{2}D\,(1+(R^2-r^2)/R^2)+mg = 2\pi r\gamma \quad \ldots\ldots\ldots \quad (3a)$$

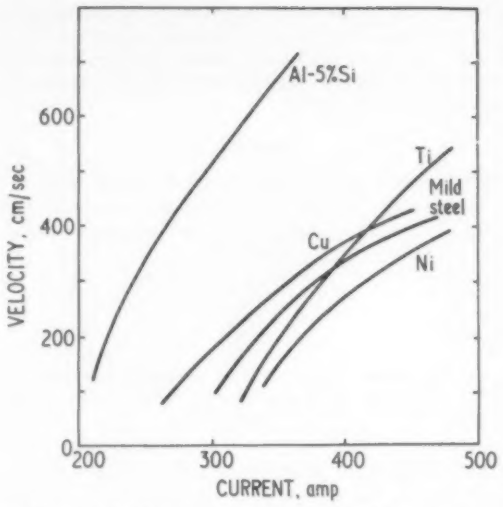
The drop size then varies more slowly with current as shown by curve (*b*) in Fig. 19*a* and the transition is not so marked. The relative contribution of the force of gravity and that of the plasma jet, to the removal of the drop, is shown as a function of current in Fig. 19*b*. At small drop sizes, *i.e.*, above about 200 amp, the contribution of gravity is negligible compared with that of the plasma jet, whereas below 100 amp the reverse is true. In the intermediate current range both forces must be considered.



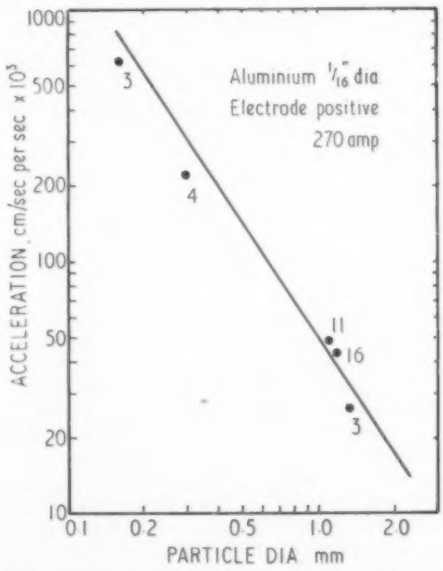

19a—*Theoretical variation of drop diameter with current:* (a) *Horizontal arc, plasma jet independent of gravity;* (b) *vertical arc with gravity aiding plasma jet*




19b—*Relative contributions of force exerted by plasma jet and that of gravity to detachment of drop hanging from vertical electrode*




20—*Theoretical velocity/current relationships for various metals*




21—*Variation of particle acceleration with diameter. (Logarithmic plot for aluminium* $\frac{1}{16}$ *in. electrode, 270 amp). (Points are averages for the number of particles indicated)*

*Variation of terminal velocity with current*

The comparison of the theoretically predicted and experimentally determined values of the force acting on an aluminium drop in free flight, and the explanation for the marked change in particle size observed at the transition current, provide evidence for the feasibility of a plasma jet mechanism of metal transfer. When the relative characteristics of a range of metals is considered, as with the transition currents, the divergence between the theoretical predictions and experimental observations shows that a complete theory would require to take account of the individual characteristics of the various metals. A further comparison can be made for the variation of the particle velocity with current. To do this it is necessary to know the distance over which the plasma jet exerts a force on the drop. In acquiring the data presented in Fig. 8, an arc length of 0·5 cm was used, but the jet continues to act on the particles after they have been projected through the hole in the plate electrode, although the velocity of the jet must attenuate rapidly. It will therefore be assumed, somewhat arbitrarily, that the effect of the jet was equivalent to the stream velocity (as measured by pressure increase at the carbon cathode) acting over a distance of 1 cm.

Inserting this value in equation (2), using the variation of drop size with current given by equation (3), and applying the relation:

$$\tfrac{1}{2}mV^2 = DL \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where $V$ is the terminal velocity acquired by the globules after travelling a distance $L$ (1 cm), the curves shown in Fig. 20 were obtained. These values of velocity and their variation with current compare with the experimental values in Fig. 8 to about the same order of agreement as obtained for the comparison of the velocity of a globule in free flight, and the variation of the transition current from one metal to another.

## Discussion

In this work the possibility of the mechanism of metal transfer being due to the action of the plasma jet has been examined, and by means of a simplified theory it has been possible to predict most of the features that have been observed experimentally. It is clear that the force exerted by the jet is sufficient to detach the globule and accelerate it across the arc and, in general, theoretical predictions agree with experimental measurements to within a factor of two or three; this is reasonable in view of the complexity of the conditions existing in the arc. It is now necessary to re-examine the experimental data and the development of the theory to see if any explanation can be advanced for the difference. It could lie in the approximations or assumptions that have been made, or in the incomplete knowledge of the details of the parameters involved.

The basic parameter is the force acting on the droplet, and this has been derived experimentally from the distance/time curve in terms of acceleration. Although acceleration is difficult to derive accurately, it is a more stringent test of the theory than a comparison of, say, terminal velocities. The latter give an optimistic impression of agreement as, for a given distance, they are dependent on the square root of the force. From the free flight data for 270 amp, although the overall spread in accelerations was from 20 to 70 $g$, part of this is due to the variation in diameter. For a droplet 0·12 cm dia. the mean acceleration was around 40 $g$ with a spread of the order of 25–55 $g$, whereas the theoretical estimate is 250 $g$. To develop the theory it was necessary to assume that the force remained constant across the arc gap, but from a statistical examination of all the flight data at 270 amp, there appears to be a significant variation of the acceleration during flight. Although there is some scatter in the results for the individual flights, the average behaviour is that the initial free flight acceleration is about double the value previously derived, on the assumption of constant acceleration, and this decreases substantially to zero by the end of the flight. This is not inconsistent with the plasma stream, which for a solid plate must be dissipated radially and hence finally does not add to the forward axial flight of the droplet. Thus the average initial free flight acceleration for a 0·12 cm droplet near the electrode could be around 80 $g$, with a spread of about 50–110 $g$, which compares not unfavourably with the theoretical value, which over-estimates by a factor of 2 or 3.

Further evidence of a change of acceleration with the flight is given by the fragmentary particles from the breakup of the neck at detachment. Many of these start at substantially zero velocity (which gives a clearer indication of acceleration change as shown by Fig. 5), and although the majority are captured by the droplet or the fluid electrode tip, a few have been found for measurement in the high-speed films. These few confirm that there was a diminution of the acceleration, a typical result for a fragment 0·03 mm dia. being initial acceleration 300 $g$ near the electrode, falling to less than half this value towards the end of the flight path.

Another possible source of error lies in the unsureness of the magnitudes of the parameters involved. The dependence of the force on the various factors can be determined from the relationship for the force acting on a sphere given in Fig. 15.

Over the range of Reynold's numbers that occur in the present work, *i.e.*, 10 to $10^2$, this relation can be expressed approximately as:

$$Re^{\frac{1}{2}} = 13/C_D \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

that is:

$$D = 14{\cdot}5\, v^{3/2} R^{3/2} \rho^{1/2} \eta^{1/2} \quad \ldots\ldots\ldots\ldots \quad (6)$$

Thus an error in the acceleration by a factor of 2 is equivalent to a change in velocity by a factor of 1·6 (from equation (1) this is equivalent to a 2·5 times variation in the current density), or a variation in the density or viscosity by a factor of 4. Clearly, of these the velocity is more likely to be incorrect, particularly since it was derived from measurements of the pressure increase at a non-consumable carbon cathode and no account could be taken of the area over which it acts and its attenuation.

An experimental observation, which has not been considered in the theoretical approach, is the considerable variation in the experimental characteristics of metal transfer for a constant setting of the equipment. This is consistent with the mechanism, however, since as already shown the plasma jet velocity is dependent upon the current density at the cathode and anode, and these are very dependent upon surface conditions.

The fact that at any one current, and hence plasma jet velocity, a range of particle sizes was observed in free flight, allows the theoretical relationship between the acceleration and particle diameter to be tested. From the fluid flow theory (equation (6) ), the force on the drop varies as $R^{3/2}$, all other parameters being assumed constant for a given arc. Since the mass of the droplet varies as $R^3$ the acceleration should vary inversely as $R^{3/2}$. Considering the spread in accelerations, no real significance can be attached to the slight differences in average acceleration for the main transfer sizes (about 0·11–0·12 cm at 270 amp) but the few fragmentary particles formed from the neck are about an order smaller in diameter with accelerations of several hundred $g$. These provide a check on the variation of acceleration with diameter, as shown by the logarithmic plots (Fig. 21) on which a line of the theoretical slope of $-3/2$ has been entered for comparison. The data, although scanty, show good agreement with the theoretical prediction based on fluid flow.

The conditions associating the plasma stream with the detachment of a droplet are less amenable to treatment. However some pointers are given here. Of

previous theories, the most prominent have been based on the pinch effect for ejecting the droplet. It should be noted here that, although the pinch effect may contribute to the neck action at an early stage when the droplet is the fluid tip to the electrode, there is no full current flow in the neck when the droplet is nearing detachment. If there were, the thin filamentary neck would vaporize in less than $10^{-4}$ sec. Nor is there any sign of rupture of the neck, such as is found when the arc length is short and the droplet momentarily short circuits the arc, or of the double arc found in the subthreshold transfer (Fig. 3), where clearly the neck gives place to a second arc between electrode and globule in series with the first from globule to plate.

However it is clear from the difference in the relative order of the experimentally measured transition currents, and those predicted on the assumption of the same plasma jet velocity and mechanism of removal taking place in every case, that a complete theory would need to take account of the individual characteristics of each metal. The plasma jet velocity could vary from one metal to another owing to the variation in anode and cathode current densities. The determination of plasma jet velocities in welding arcs while metal transfer is taking place is the main requirement for the further development of the theory. In addition, the geometry of drop removal could change from one metal to another, and evidence for this is available from the work of Lesnewich[1] who showed that with mild steel the electrode end exhibited a marked taper, compared with the geometry of aluminium transfer shown in Figs. 1–4 of the present paper. In addition, the theory presented for the force acting on the drop as it forms on the end of the electrode is weak, in that it has been possible to make only a rough estimate of the force acting. Probably the best approach to this problem would be to investigate similar geometrical, but more amenable, systems, *e.g.*, scaled-up models in liquid streams, so as to obtain a basic relationship for the force acting on a drop on the end of a wire, similar to that presented for the free drop in Fig. 15.

One further point requires some explanation: the fact that the globule velocities determined from the trajectories through a plate hole were consistently greater than the flight measurements for a bead run (compare Figs. 7 and 9 respectively). The reason for this was shown by high-speed cine-photography of the trajectory method. Using a water-cooled copper plate with a central hole and a transverse slot, the arc could be operated stably for periods up to a minute and the transfer filmed as it progressed from the electrode towards the plate, through the hole (viewed through the slot) and out beyond, with the carbon arc backing off light to silhouette the transfer. Flight measurements showed that there was appreciable acceleration, both in the hole and beyond it, as well as between the electrode and plate. Typical velocities at 200 amp were: initial, 130; at plate, 250; exit plate hole, 300; 1 cm from hole, 340; and 3 cm from hole, 370 cm/sec. Thus the trajectory velocity method gives results about $1\frac{1}{2}$ times the plate final velocity.

## Conclusions

The plasma jet mechanism of metal transfer has been shown to be feasible by:

(1) The existence of plasma jets in welding arcs, as demonstrated by experiments in which particles injected into the arc gained a high velocity, and measurements of the back reaction pressure on the cathode.

(2) The experimental observations that the vapour emanating from a metal globule in flight across the arc travelled in the direction of the jet, and the globule accelerated while it was in free flight and was thus in contact only with the arc plasma.

(3) The reasonable agreement obtained between the theoretical predictions and the experimental determinations of the variation of the free flight velocity of the particle, with distance and current, and the acceleration, for aluminium.

(4) The explanation which the variation of the plasma jet velocity with current density affords for the existence of a transition current, and the marked change in the size of the globule associated with it.

## Acknowledgments

The authors wish to thank Professor Rollason, Head of the Department of Industrial Metallurgy, University of Birmingham, for his interest and encouragement throughout the course of this work, the Director of the Atomic Energy Establishment at Harwell for financial support, and Dr. H. G. Taylor, Director of the Electrical Research Association, for permission to publish researches carried out under Committee Z/H.

They are also indebted to Mr. L. A. King of the Electrical Research Association for help and advice on the fundamental properties and structure of the arc.

## REFERENCES

1. A. Lesnewich: *Welding J.*, 1958, vol. 37, p. 418*s*.
2. H. C. Ludwig: *Welding J.*, 1957, vol. 36, p. 235.
3. J. Sach: *J. Welding Industry*, 1939, vol. 7, p. 234.
4. L. J. Larson: *Welding J.*, 1942, vol. 21, p. 107.
5. L. A. King: *Appl. Sci. Res.*, 1955–6, vol. 5B, p. 189; *Spectrochem. Acta.*, Proc. Int. Spectro. Colloquia, Amsterdam, 1956, p. 152.
6. H. Maecker: *Z. Physik*, 1955, vol. 141, p. 204.
7. J. C. Needham and A. A. Smith: *Brit. Welding J.*, 1958, vol. 5, p. 66.
8. E. S. Pearson and H. O. Hartley, "Biometrika Tables for Statisticians", vol. 1, p. 61, Cambridge Univ. Press, 1956.
9. G. E. Doan and R. E. Lorentz: *Welding J.*, 1941, vol. 20, p. 103.
10. G. Busz-Peuckert and W. Finkelnburg: *Z. Physik*, 1954, vol. 139, p. 212; 1955, vol. 140, p. 540; 1956, vol. 144, p. 244; 1956, vol. 146, p. 655.
11. H. Schlichting: "Boundary Layer Theory", Pergammon Press Ltd., 1955.
12. R. Wienecke: *Z. Physik*, 1955, vol. 143, p. 128.
13. I. Amdur and E. A. Mason: *Physics of Fluids*, 1958, vol. 1, p. 370.

# HEAT TRANSFER FROM ARCS

*By J. B. Wilkinson and D. R. Milner*

*The energy distribution for arcs between a non-consumable tungsten cathode and a water-cooled copper anode has been determined in atmospheres of argon, nitrogen, helium, and hydrogen. In general, 80–90% of the energy expended in an arc of this type has been found to go to the anode, with the remainder divided between the cathode heating and the heat carried away by the gas, which leaves the arc region at temperatures of the order of 1000–6000°K.*

*The main part of the investigation has been directed to the examination of the heat flow to the anode, which comprises the electron heating, together with heat transfer from a plasma jet which originates from the constriction of the current caused by the cathode spot. The velocity and diameter of the jet in argon arcs have been determined at the anode by comparing the pressure increase it creates with that caused by jets of known velocity and extent. It has been found that the jet velocity is of the order of $10^4$ cm/sec, and the diameter a few millimetres. The intensity of the jet in dissociable gases made measurements impossible because of the rapid erosion of the apparatus. For argon arcs the heat transfer from these high-velocity, high-temperature jets has been separated from the heating caused by the electron stream in experiments with a three part anode, in which a centre section received the electron heating together with some plasma jet heating, while a surrounding annulus was heated only by the plasma jet. Conventional heat transfer concepts have been applied with some success to the interpretation of the data on heat transfer from the jet to the cooled anode.*

*It is suggested that jets of this type in dissociable gases are responsible for deep-penetration effects in welding.*

## Introduction

THIS work, which is part of a programme of research into the fundamentals of arc welding, is concerned with the mechanism by which electrical energy is converted into heat in the arc, and with the transfer of heat to the electrodes and the arc atmosphere. This problem is important in welding because it controls the formation of the weld pool, the melting of a consumable electrode, and the reactions taking place between the high-temperature gases in the arc atmosphere and the molten weld metal. A simple system was chosen for investigation, *i.e.*, the inert-gas shrouded non-consumable electrode process with a water-cooled copper anode, and the total energy dissipated in the arc has been separated into the contributions to the cathode, the anode, and the arc atmosphere. The present state of knowledge of arcs has been discussed in another paper in this series,[1] so that it is only necessary to summarize here those aspects which are intimately related to the present work.

The major emphasis of the work has been on heat transfer to the anode. The heat entering the anode comprises the energy of the current-carrying electron stream and heat transfer from the arc column. The electron contribution to the anode heating $H_a$ is given by the thermal energy of the electrons at the high temperature of the column, $3kT/2e$, plus that acquired as a result of acceleration through the anode drop $V_a$, and the heat of condensation $I\phi$, where $\phi$ is the work function of the anode material and $I$ is the current. Thus:

$$H_a = I(\phi + V_a + 3kT/2e) \quad \ldots\ldots\ldots\ldots \quad (1)$$

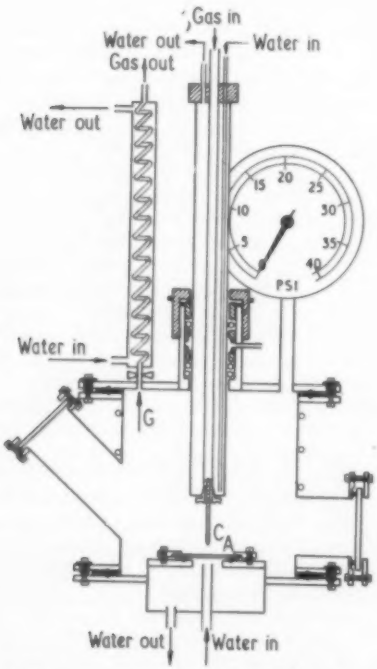
This is the amount of heat which enters the anode when there is no heat transfer from the arc column, and should therefore be given by extrapolation of anode heating curves back to zero arc length. It has usually been assumed that this contribution remains constant with increasing arc length, and that therefore the additional heat received by the anode as the arc length is increased is contributed by heat transfer from the arc column. But recent work by Busz-Peuckert and Finkelnburg[2] and data presented in the present paper, show that the anode drop varies with both the current and arc length. The energy transferred from the arc column to the anode is determined by the contributions of conduction and convection, and this in turn is dependent upon the gas flow in the arc. Maecker[3] has shown that the restriction of the current to a spot at the cathode causes an arc to act as a pump, so that cold gas is sucked into the arc and heated to form a high-velocity, high-temperature plasma jet which impinges on the anode. Maecker[3] and Wienecke[4] demonstrated the existence of this jet and determined its characteristics in the high-current carbon arc, while the present work shows that it exists also in the non-consumable tungsten electrode inert-gas arc. In another paper in the present series by Salter and Milner,[5] mass transfer from the jet to the anode has been considered for the case in which the gas reacts with the metal, the system oxygen–titanium having been chosen for investigation;

Manuscript received 27th November, 1959.
The authors are in the Department of Industrial Metallurgy at Birmingham University.

part of the aim of the present work has been to investigate the analogous case of heat transfer to the weld in non-reacting systems. Attempts have therefore been made to separate experimentally the electron heating of the anode from the plasma jet heating and to interpret the results by the application of a theory of heat transfer from a hot jet to a cold plate.

No satisfactory energy balance can be established for the cathode, for the basic principles of the physics of the cathode have not yet been established. Heat is imparted to the cathode by the ion current, but neither the accommodation coefficient of the ions nor the proportion of the current at the cathode which is carried by ions is known. In these circumstances it appears unlikely that any substantial progress can be made towards elucidating the role of cathode heating in welding arcs, so that this aspect has received relatively little attention in the present work.

The amount of energy dissipated in the arc column is related to the plasma temperature needed to maintain that degree of ionization of the arc atmosphere which will permit the passage of the current. A high ionization potential, or a high thermal conductivity, which increases the rate of heat loss from the column, therefore means a high rate of energy dissipation and arc column voltage gradient. An energy balance has been set up for an arc burning in a tube in which the heat loss is entirely by conduction, and for an unconfined arc with heat losses by conduction only (see review paper in present series by Milner, Salter and Wilkinson[1]), but an energy balance for the free burning arc, in which a plasma jet exists, has yet to be made.




1—*Controlled atmosphere chamber in which arc was operated and relevant heat flow measurements made*

In the present work, energy balances have been measured, and the anode heating has been related to the existence of plasma jets, in non-consumable electrode arcs. The relative behaviour of a monatomic gas (argon), and a diatomic gas (nitrogen), has been investigated, and this has been supplemented by a limited number of measurements on helium and hydrogen arcs.

A problem inherent in work of this type is that in a practical welding system it is very difficult to obtain sufficiently stable conditions for making accurate and reproducible measurements. The alternative is to use water-cooled electrodes to improve stability and facilitate the application of the principles of continuous flow calorimetry. As stated previously, the major emphasis in the present work has been on the investigation of the anode heating, and the separation of the relative contributions of the electron stream and the plasma jet. This provided a further reason for using a water-cooled system since no means for the determination of the contribution of the plasma jet could be envisaged without the use of a water-cooled anode, and even with such an anode it was not found possible to measure the characteristics of the plasma jet in nitrogen because of the intensity of its action. The quantitative behaviour of a water-cooled anode system can be expected to differ in some respects from that of a welding system, and this point is considered in the discussion in relation to the results that have been obtained.

## Experimental Work

The experimental work is divided into two sections. The first deals with the determination of total energy balances for arcs in argon and nitrogen, together with a limited number of measurements on hydrogen and helium arcs. The second section describes an investigation of the velocity, extent, and heat transfer from the plasma jet.

### Total Energy Balances

The apparatus used to measure, simultaneously, the heat inputs to the arc anode and cathode and the heat carried away from the arc region by the effluent gas is shown diagrammatically in Fig. 1. These measurements were all made by using the principles of continuous-flow calorimetry, the water flow rates to the anode (marked *A* in Fig. 1), the cathode *C*, and the effluent gas heat exchanger *G* being separately metered by rotameters, and the temperatures of the inlet and outlet flows being each measured by 0–50°C. mercury thermometers, calibrated in $\frac{1}{10}$°.

In general, except where otherwise stated, d.c. arcs between a thoriated tungsten cathode and a copper anode were studied. The cathode was held by a converted commercial 600-amp argonarc machine-welding torch, *via* a brass collet, through which passed a flow of the gas in which the arc was burning. The torch, and hence the cathode, was cooled by the aforementioned metered stream of water, and was movable in a vertical direction, passing through a gas-tight Wilson seal on the top portion of the apparatus. A vernier gauge strapped to this seal and to the torch

enabled measurements of the anode-cathode distance to be made to within about 0·2 mm.

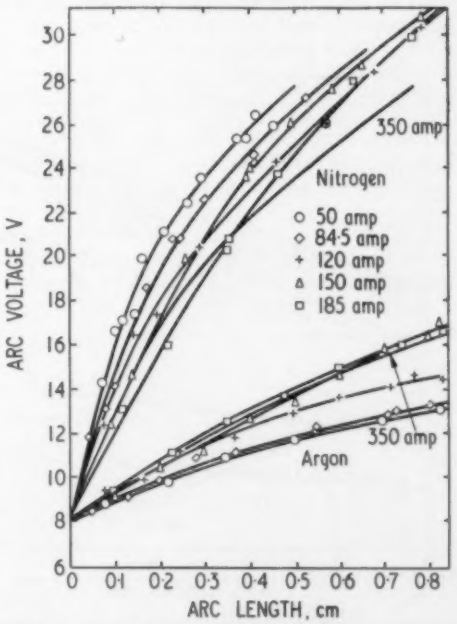
The anode *A* was a disc, generally $\frac{1}{4}$ in. thick and approximately $2\frac{1}{2}$ in. dia., which was clamped to an O ring by a steel ring, bolted to the lower portion of the apparatus. The disc was cooled by a jet of water impinging on the back, directly beneath the arc. When measurements were made on high-current (250–350 amp) or high-voltage (hydrogen) arcs, it was found necessary to make the central portion of the anode disc much thicker than $\frac{1}{8}$ in. owing to the powerful cratering action of such arcs.

The gas flow rate into the chamber was measured by a rotameter, and the heat carried away from the arc region by the effluent gases was extracted in a heat exchanger, through which flowed the metered stream of water. The same stream was used to cool the walls of the chamber, which were heated by the gas carried away from the arc region. The amount of energy which the chamber wall received by radiation from a 12 V, 100 amp argon arc was estimated from the heating of a piece of blackened platinum foil to be approximately 3 W, a negligibly small proportion of the total arc power.

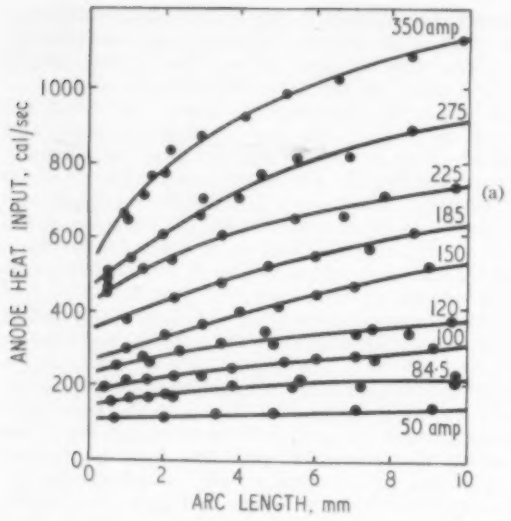
It was found that some precautions in the experimental techniques were necessary to obtain reproducible results. However, when the procedure to be described was adopted, the measured heat and the power consumed usually agreed to within 3% or less.

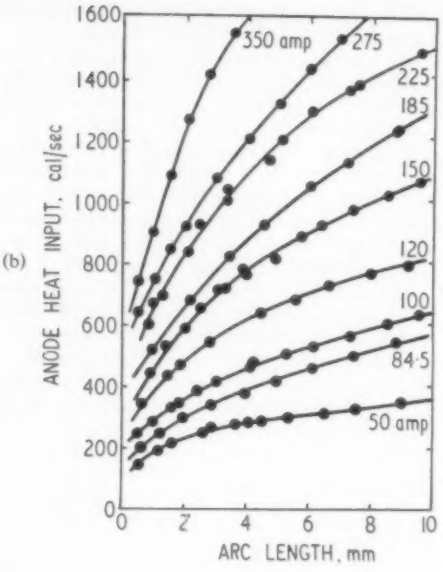
To prevent the cooling water from picking up heat from the surrounding atmosphere—a contribution which can amount to 100 W on a warm humid day—the water was raised almost to room temperature before being fed to the apparatus by first passing it through a heat exchanger, through which atmospheric air was forced by a 15 in. dia. fan. The anode was cleaned, degreased, and scratch-brushed, and the cathode tip was ground to a point before each experiment. The gas in which the arc was to burn was allowed to flow into the chamber for about 20 min before the arc was struck, so as to flush out any traces of air, and the cooling water was allowed to run for a similar length of time so that equilibrium water inlet and outlet temperatures could be attained. The arc was struck by a spark from a high-frequency spark generator giving 5,000 V at 300 kc/sec, the power sources for the arc being 300 or 500 amp generators, or occasionally two of these in series if a high-voltage arc was being studied. The arc was run at a pre-set length and current for 5–10 min before the values of arc voltage and water temperatures and flow rates were read off, to ensure that equilibrium had been attained. In most cases, it was then permissible to change the parameter being studied (arc length or current, etc.) without switching off the arc, but for arcs in hydrogen, or high-current (>250 amp) arcs in nitrogen or argon, it was necessary (because of the intense cratering effect on the anode) to switch off and find what the arc length had been by lowering the cathode to touch the bottom of the crater and then reading off this position on the external vernier gauge. Provided that these precautions were observed and that the experimental procedure described was followed, results were obtained which were reproducible to within about 10% from one occasion to another. This lack of reproducibility of results obtained on separate occasions is a constant source of trouble in arc work, and the results quoted in the following sections represent the mean values from several (usually three, occasionally more) experiments.

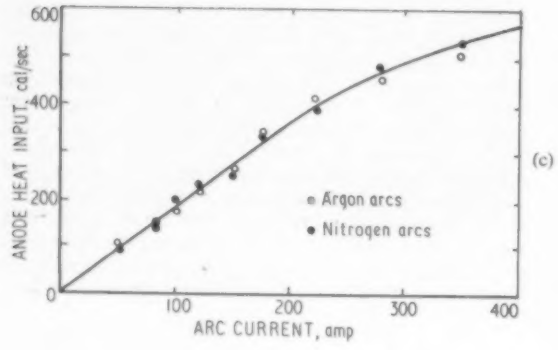
By using the experimental methods described, the arc voltage (Fig. 2), the heat inputs to the anode and cathode (Figs. 3 and 4), and the heat carried away from the system by the effluent gases (Fig. 5), were measured as a function of arc length, for argon and nitrogen arcs in the current range 50–350 amp. From these results the distribution of the heat has been derived and is presented in Fig. 6, which shows that the heat entering the anode accounts for 80–90% of the total energy dissipated in the argon arc, and is some 5–10% (depending on the arc length) greater in the nitrogen arc. The heat given to the cathode amounted to only a few percent of the total energy and was much the same for both gases. The major difference in the behaviour of the two gases was in the amount of energy converted into heat in the arc column, and in the efficiency with which this energy was transported to the anode. The heat entering the anode comprises the electron heating and the heat transfer from the arc column. The arc voltage at zero arc length, Fig. 2, and the heat input to the anode at zero arc length, Fig. 3*c*, show that the electron heating is the same for both gases. Figure 2 shows that approximately three times as much energy was expended in the column of the nitrogen arc as in that of the argon arc, but even so the heat content of the nitrogen leaving the chamber was less than that of argon (*see* Fig. 5). The efficiency of heat transfer to the anode from the arc atmosphere is difficult to estimate accurately, since the contribution to the anode heating of the electron stream, which must be subtracted from the total anode heating to obtain the arc atmosphere



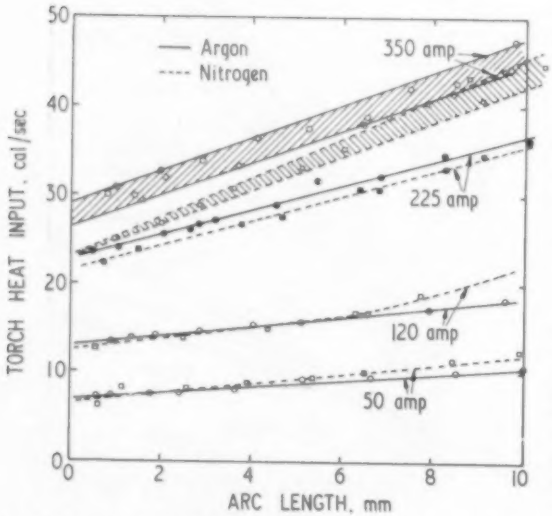

2—*Arc voltage as a function of arc length for argon and nitrogen arcs in current range 50–350 amp*



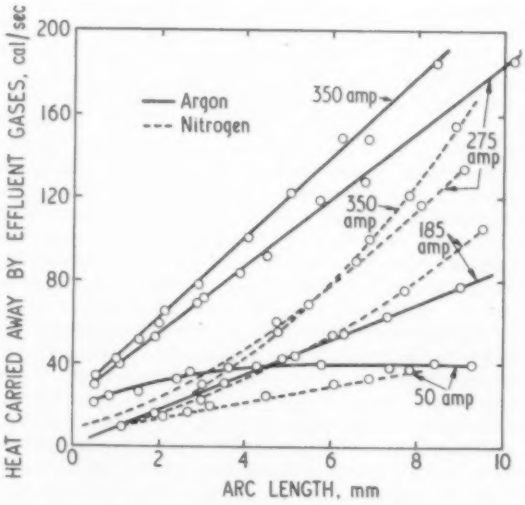



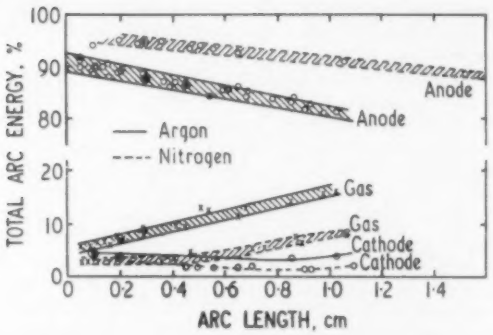

3—*Heat input to anode as a function of arc length for current range 50–350 amp: (a) Argon arcs; (b) nitrogen arcs; (c) 'zero arc length' value obtained by extrapolation*




4—*Heat input to cathode and cathode holder (torch), as a function of arc length and current*




5—*Heat carried away by effluent gases, together with that received by chamber walls, as a function of arc length and current*




*6—Proportion of total energy expended in the arc that is transported to anode and to cathode, and is carried away by effluent gas*

heat transfer, is not known. As will be shown later, the simple assumption that the anode drop, and therefore the electron heating, remains constant with arc length (and is therefore equal to the zero arc length value), is not true, but at long arc lengths, where the electron heating is small compared with the gas heating, this effect can be ignored as a first approximation and the heat transfer efficiency is then found to be 55–75% for argon and 75–90% for nitrogen.

To supplement the measurements on argon and nitrogen arcs, attempts were made to determine energy balances for helium and hydrogen arcs. Only two determinations (at 100 and 200 amp) were made with helium in view of its high cost, and these are presented in Fig. 7. The general distribution of the heat was similar to that in the argon and nitrogen arcs, with 90–95% of the total energy entering the anode and only a few percent going to the cathode. But the amount of energy entering the anode at zero arc length was greater, being approximately 1·5 times that of the argon and nitrogen arcs, suggesting that the electron heating (and therefore the anode drop) is higher in the helium arc. The rate of dissipation of energy in the arc column was intermediate between that of argon and nitrogen, *i.e.*, 1·5 times the argon column gradient, compared with the factor of 3 for nitrogen.

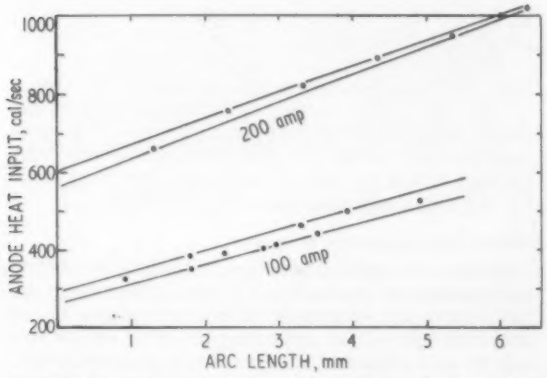
The investigation of the hydrogen arc proved to be most difficult, since even with the most efficient water cooling it rapidly eroded the anode causing the arc length to change continuously and giving an unstable arc. It was possible to obtain any sort of control of the cratering action only by using currents of less than 100 amp, and even then measurements had to be made and the arc immediately extinguished so that the depth of the crater, and hence the arc length, could be determined. Also measurements had to be limited to arc lengths greater than 3 mm, and reproducibility was poor. The best results that could be obtained are presented in Fig. 8, and these show that again about 90% of the total arc energy entered the anode. The expenditure of energy in the arc column was very high, about 6 times that of the argon arc, compared with the 3 times factor in the nitrogen arc, and just over twice as much heat went into the cathode, but the results were not sufficiently comprehensive to allow of further comment beyond these broad generalizations.

## Plasma Jet Measurements

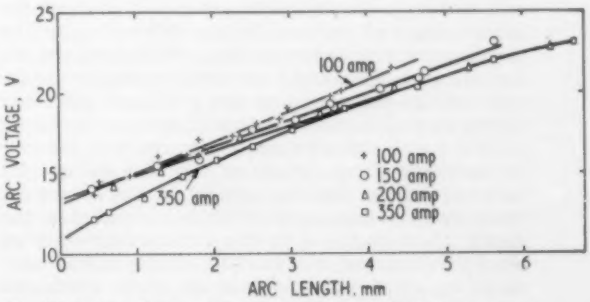
This section deals with the detection of plasma jets in the welding arc, the estimation of the velocity and diameter of such jets, and the measurement of the contribution they make to the anode heat input. The properties of the jet which determine heat transfer to the anode are its velocity, diameter, and temperature in the anode region. The velocity and extent of the jet were determined from the pressure increase at the anode, which was measured by connecting a small hole in the anode to an inclined manometer, and traversing the anode (and hence this hole) under the arc. The high-temperature region created by the jet at the anode has been investigated by photographically recording changes in the luminous area. The problem of determining how much of the total heat entering the anode is due to the electron stream and how much to the plasma jet has been approached experimentally by the physical subdivision of the anode into two or three parts, in which one part carries entirely the electron current and some of the plasma jet heating, while the other section absorbs only plasma heating.

### Plasma jet velocities

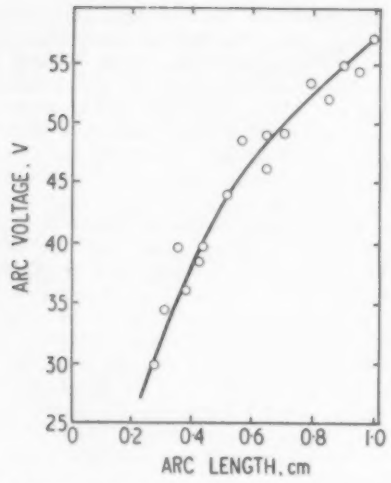
The existence of a plasma jet depends on a constriction in the arc, such as a cathode spot, and a



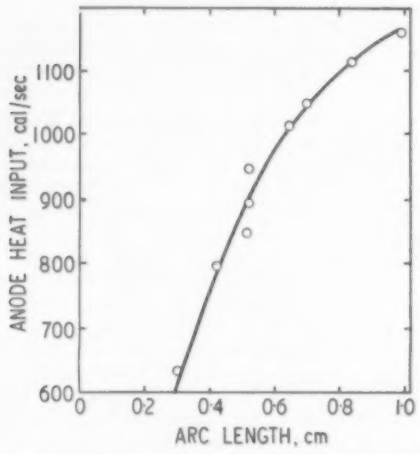

*7a—Heat input to anode for arcs in helium, as a function of arc length and current*




*7b—Variation of arc voltage with arc length for helium arcs at currents between 100 and 350 amp*




*8a—Heat input to anode of 100-amp arc in hydrogen, as a function of arc length*




*8b—Variation of arc voltage with arc length for 100-amp hydrogen arc*

current density gradient, and these can be inferred from the external appearance of the arc. Thus Fig. 9*a* shows a photograph of a normal 100-amp argon arc with a clean, water-cooled copper anode, in which the constriction was provided by the cathode spot. The plasma jet acts by sucking gas into the arc from around the cathode and causing it to form a high-temperature, high-velocity jet, travelling along the arc axis, and impinging on the anode. The anode does not appear to possess a well defined current-carrying spot and any jet emanating from the anode region is diffuse and slow moving, so that the cathode jet can thus override it and make its presence felt as a pressure on the anode. The existence of plasma jets and their effect on the appearance of the arc was demonstrated very clearly by an arc operating with an anode which was contaminated by a piece of oxide; this caused a constriction at the anode, so that an anode jet was formed of a comparable magnitude to the cathode jet. The two jets interacted in the centre of the arc to give the effect shown in Fig. 9*b*.

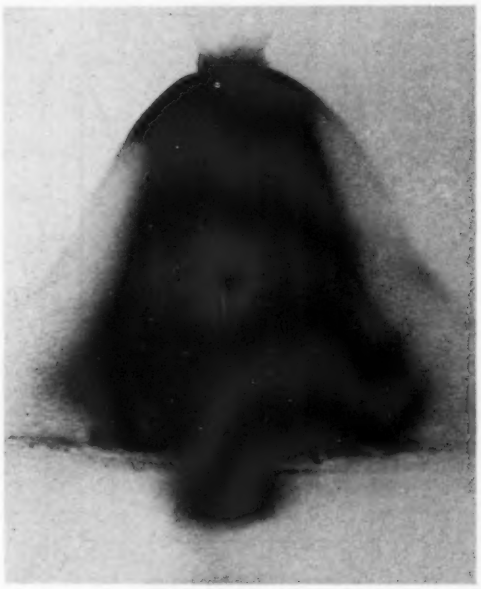
Estimates of the velocity of the cathode plasma jet at the anode in argon arcs at currents between 50 and 200 amp were made by measuring the pressure distribution across the anode plate and comparing this with that caused by a jet of gas issuing from a tube of known bore. This was done by connecting a small hole (0·040 or 0·015 in. dia.) in the anode to an inclined manometer, and traversing this hole beneath the arc in steps of 0·005–0·020 in. Figure 10*a* shows the pressure distribution across the anode plate due to 3-mm long argon arcs, and Fig. 10*b* shows the effect of arc length on the pressure. For the determination of velocity, the pressure distribution due to a jet of oxygen impinging on the anode was determined for a number of tube diameters and velocities to find one that gave a similar result to the plasma jet. Figure 11 shows that roughly similar distributions were obtained with a 100-amp argon arc and 1-mm dia., 3 mm long jet of oxygen flowing at 20 m/sec. From Bernoulli's theorem $\rho_1 v^2_1 = \rho_2 v^2_2$ where $\rho$ and $v$ are the respective densities and velocities of the jets, so that the plasma jet velocity can be found if its density (*i.e.*, its temperature) is known. If a temperature of 10,000°K. is assumed, the velocity of the 100-amp jet is $2{\cdot}2 \times 10^4$ cm/sec. The variation in the maximum pressure at the anode was determined as a function of the current and converted to a velocity variation using the above density, to give the result shown in Fig. 12. (If the fact that the plasma jet temperature increases with current had also been taken into account, the rate of increase with current would have been greater.)

This curve is similar in form to that obtained by Maecker,[3] who measured the pressure increase at a carbon cathode of an arc in air, but the magnitude of the velocities is higher than that inferred from Maecker's pressure measurements by a factor of 2. This is probably because the cathode spot is larger with a carbon, than with a tungsten, cathode; in addition, Maecker increased the size of the cathode spot, thus decreasing the current density on which the velocity is dependent, by boring a 1 mm hole down the centre of the cathode so as to make the necessary pressure measurements.

It is unfortunate that a similar determination of plasma jet velocity could not be made with nitrogen arcs, because of their cratering action on the anode plate. This intense cratering effect is presumably indicative of the existence of a more intense jet, *i.e.*, higher velocity and higher temperature acting over a smaller area, than occurs in argon arcs. King[6] has shown that the free-burning arc in dissociable gases develops an intense high-temperature inner core through which the current flows, and this must mean in turn that the plasma jet is more confined.

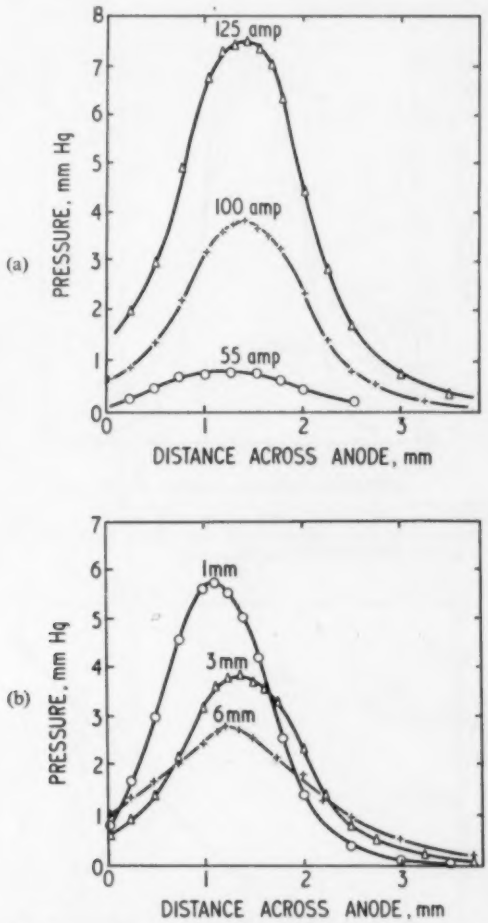
#### Zone of high temperature at anode

Where the high-temperature, high-velocity plasma jet impinges on the anode, it creates a high-temperature region, the magnitude of which is related to the characteristics of the impinging jet. The size of this region, and its variation with current and arc length, was investigated photographically. The assumption was made that the outline of the arc, which was visible



*9a—Normal 1 cm, 100-amp argon arc*

*9b—Argon arc in which oxide spot on anode causes an anode plasma jet which collides with jet coming from cathode*



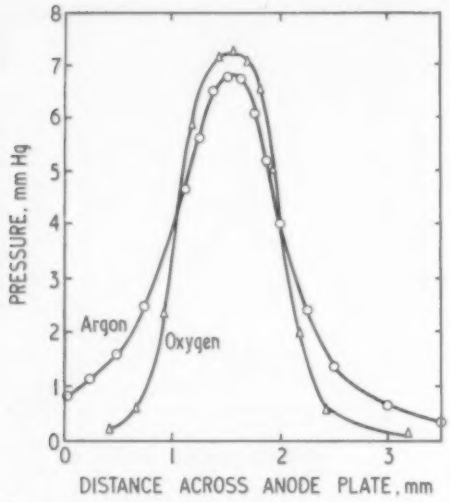

*10—Pressure distribution across anode plate:* (a) *From argon arcs at various currents, with constant arc length of 3 mm;* (b) *from 100-amp argon arc at various arc lengths*

on a series of photographs made under constant conditions, would show the variation of a particular isotherm. The effect of arc length is shown in Fig. 13, from which it can be seen that at first there was a rapid increase in the diameter of the arc at the anode, but that for arc lengths in excess of 1 cm in nitrogen, and 2 cm in argon, the arc diameter remained constant. It was found that the effect of current was to produce a linear increase in the high-temperature area (*i.e.*, the square of the diameter) adjacent to the anode (Fig. 14).

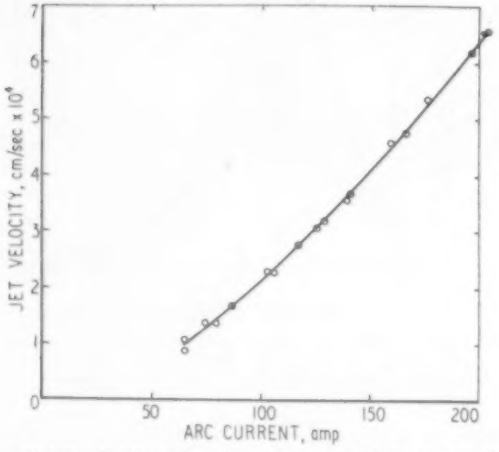
**Heat transfer from plasma jet**

The logical extension of the work described was to separate the heat, transported to the anode by the plasma jet, from that transferred to the anode by the electron stream. This was attempted by constructing a multi-component anode so that the electron current and some heat transfer from the plasma jet was carried by a central section, and only heat transfer from the jet went to the outer section.

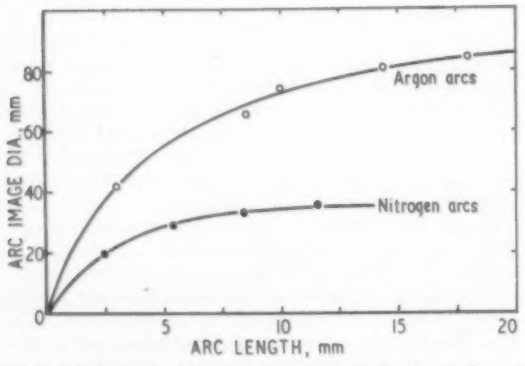
It was not sufficient, however, to make the anode of two parts, since, although the outer section received heat only from the jet, it was not possible to determine the area over which this heat was received. A three-component anode was therefore constructed, in which the central section was surrounded by a narrow inner annulus and a further larger outer annulus, as shown in Fig. 15. The distribution of the anode heating for



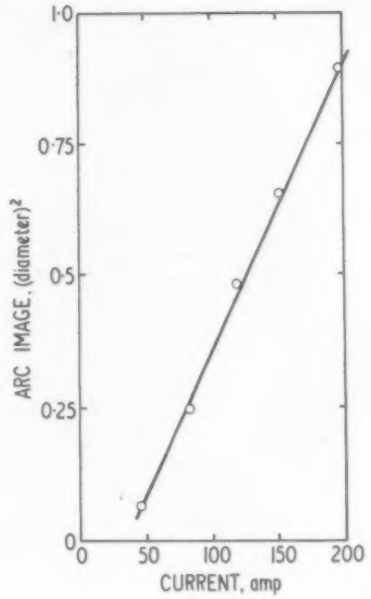

11—*Pressure distribution across anode plate from a 100-amp, 3-mm argon arc, compared with that arising from 20 m/sec, 1 mm jet of oxygen, 3 mm from plate*



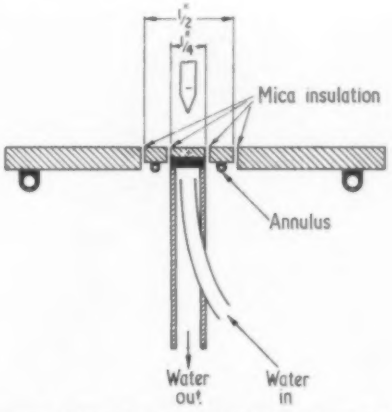

12—*Variation in plasma jet velocity at anode with arc current, for 3 mm long argon arcs*




13—*Variation in arc image diameter (magnification 6·5) with changes in arc length for 100-amp argon and nitrogen arcs*

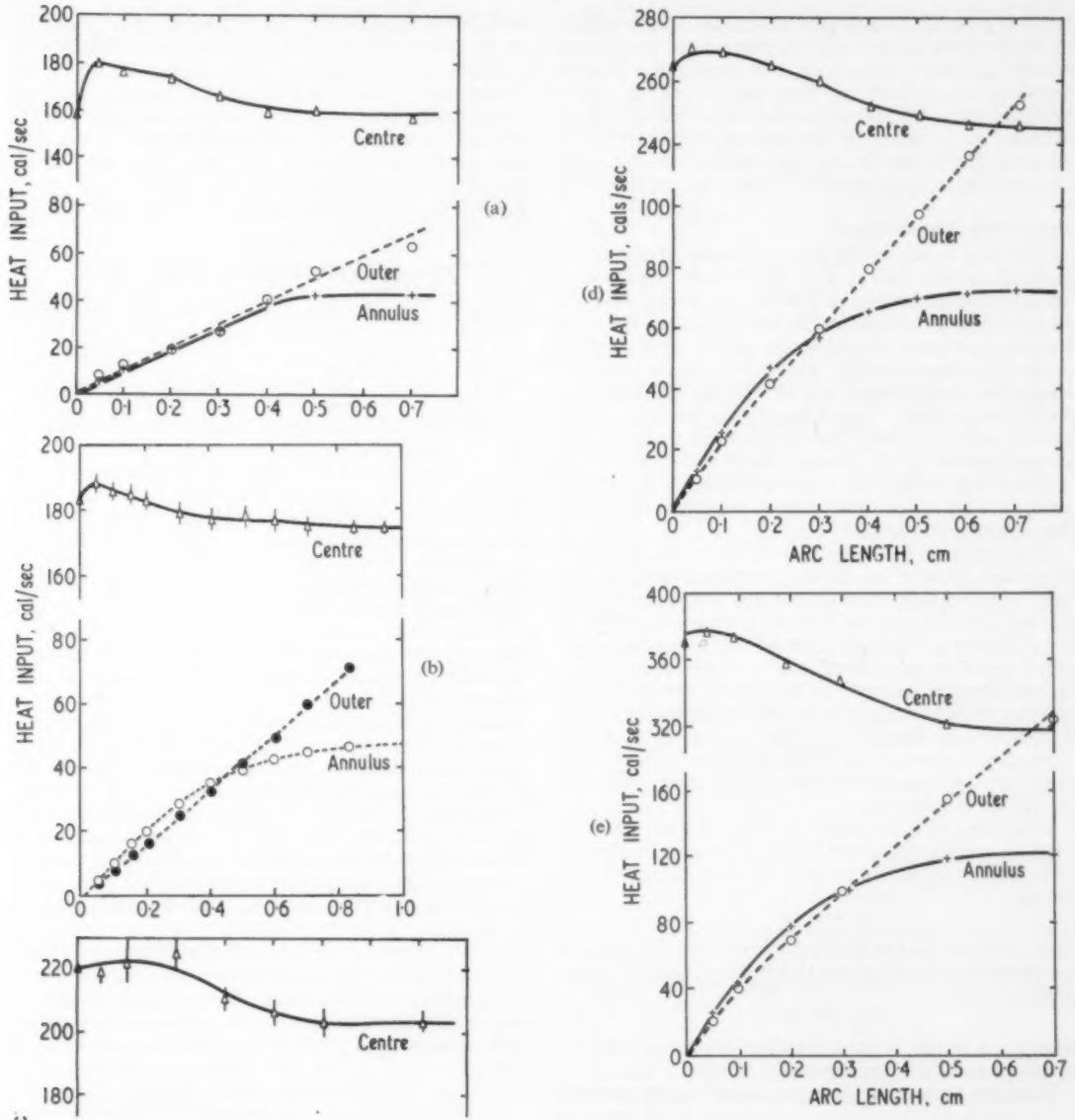



14—*Variation in square of arc image diameter with arc current for 3-mm long argon arc*




15—*Diagram of divided anode used for determination of relative contributions of electron heating and heat transfer from plasma jet*

this type of anode in argon arcs for the current range 85–200 amp was then found to be as shown in Fig. 16. From these figures it can be seen that the heat input to the centre portion of the anode fell off with increasing arc length, (suggesting that the anode drop also decreased) until it reached a steady value at arc lengths greater than 0·5–0·75 cm. This was attributed to the fact that as the arc length was increased the plasma jet broadened out (and its velocity and temperature at the anode decreased), so that, whereas at small arc lengths the jet impinged entirely on the central portion of the anode, at longer arc lengths it impinged also on the outer annulus. At about 0·5 cm, where the heat input to the inner annulus became constant, the jet completely covered the inner annulus. Unfortunately it was not possible to carry out similar measurements for




16—*Heat input to three parts of divided anode as a function of current and arc length*: (a) *85 amp;* (b) *100 amp;* (c) *120 amp;* (d) *150 amp;* (e) *200 amp.* (*The total anode heat input is the same as that given by Fig.* 3a, *so that zero arc length heat input, which could not be derived by extrapolation in this experiment, is the value given by Fig.* 3c)

arcs in nitrogen, as the intense cratering action of the nitrogen arc caused the disintegration of the central section of the anode.

### Interpretation of Experimental Results

From the measurements of the heating of the three-part anode and of the characteristics of the plasma

jet, it is possible to estimate the relative contributions of the electron stream and the plasma jet to the total energy received by the anode in an argon arc. Thus the annulus receives heat only from the plasma jet, and an understanding of the mechanism involved allows an estimate to be made of the amount of heat transfer received from the jet by the central section, thus determining the contribution of the electron stream.

**Heat transfer from plasma jet**

The heat input to the inner annulus of the three-part anode was seen in Fig. 16 to reach a maximum value above arc lengths of 0·6–0·7 cm. It was shown in Fig. 13 that as the arc length was increased the high-temperature area created at the anode by the jet increased and the heat input attained its maximum value when the visible boundary of the arc expanded to cover the annulus. Unfortunately no investigation of heat transfer from jets, that would allow a comparison to be made with the present work, is known to the authors, but Woodrow[7] has carried out a theoretical analysis which forms the basis of the interpretation of the experimental results.

The mechanism of heat transfer from the jet is that of forced convection, in which transfer through the bulk of the rapidly moving hot gas occurs readily. At the surface of the anode there is a 'stagnant boundary layer', and it is the conduction of heat across this layer which controls the rate of heat transfer to the anode. In problems of this type an analysis of the conditions existing at the boundary layer, and of the factors which control them, is too complex, and a less detailed approach is adopted in which the principles of similarity are applied to formulate relationships between groups of variables.

Following this method, the rate of heat transfer from the plasma jet to the anode is made proportional to the difference in temperature between the anode and the jet:

$$Q = h \,.\, \Delta T \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $h$ is the heat transfer coefficient and is related to the properties of the gas by three dimensionless groups according to:

$$Nu = f(Pr.\ Re.) \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where $Nu$ is the Nusselt number; $Pr$ is the Prandtl number; and $Re$ is the Reynolds number.

Inserting quantities for these dimensionless groups:

$$\frac{h \,.\, d}{k} = f\left[\left(\frac{\eta C_p}{k}\right), \left(\frac{v\rho d}{\eta}\right)\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

where $d$ is the jet diameter; $k$ the gas thermal conductivity; $\eta$ the gas viscosity; $C_p$ the gas specific heat at constant pressure; $v$ the velocity of the jet; and $\rho$ the gas density.

The problem is now to determine the form of the function. In many cases of laminar flow, it has been found experimentally that equation (4) can be written as:

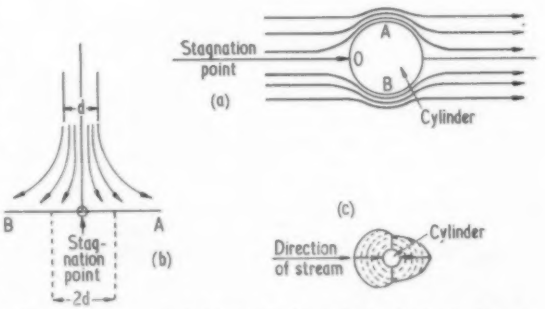
$$\frac{hd}{k} = \text{const.} \left(\frac{\eta C_p}{k}\right)^{\frac{1}{3}} \left(\frac{v\rho d}{\eta}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots \quad (5)$$

Woodrow, adopting an analytical approach, arrived at the conclusion that the form of equation (5) was correct, and that for heat transfer within a distance from the stagnation point equal to the diameter of the jet, the constant was of the order of 0·8, with a possible error of 40%, but for heat transfer outside these limits the value of the constant could not be derived analytically. A comparison between the theoretically predicted rate of heat transfer and that determined experimentally can best be made for the 200-amp arc, since it is necessary to know the temperature distribution, and for this arc it has been determined by Busz-Peuckert and Finkelnburg.[2] From Table I the velocity and diameter of the plasma jet at an arc length of 0·6 cm are estimated as $4{\cdot}7 \times 10^4$ cm/sec and 0·3 cm respectively. Since the internal diameter of the annulus was 0·63 cm, the conditions of heat transfer were outside those to which the constant derived by Woodrow pertains. In the absence of more relevant information, the change in the value of the constant can be estimated roughly by comparison with heat transfer to a cylinder. When a cylinder is placed in a gas stream there is a stagnation point $O$, while the gas flow is parallel to the outer surface of the cylinder at $AB$, Fig. 17. Similarly, with a jet impinging on a plate there is a central stagnation point, while at a distance from the centre the gas flow has been diverted to become parallel to the surface of the plate. The sketches in Fig. 17 attempt to illustrate the similarity of gas flow in the two systems. Data presented by McAdam[8] shows that the rate of heat transfer at the stagnation point of the cylinder is about 2·5–3 times greater than that where the gas flow is parallel to its surface. If the same relationship is assumed to apply to the case of a jet, then the constant in equation (5) is

**Table I**

**Plasma jet characteristics at various currents**

| *Arc Current, amp* | *Arc Length, cm* | *Plasma Jet Dia., cm* | *Plasma Jet Velocity cm/sec* $\times 10^4$ |
|---|---|---|---|
| 100 | 0·3 | 0·15 | 2·2 |
| | 0·6 | 0·15 | 1·6 |
| | 0·9 | 0·15 | 1·3 |
| 150 | 0·3 | 0·225 | 4·95 |
| | 0·6 | 0·225 | 3·6 |
| | 0·9 | 0·225 | 2·9 |
| 225 | 0·3 | 0·34 | 8·7 |
| | 0·6 | 0·34 | 6·4 |
| | 0·9 | 0·34 | 5·8 |




17—*Fluid flow around:* (a) *A cylinder and* (b) *a jet impinging on a plate. In both cases there is a stagnation point* O, *on either side of which the flow is directed at an angle to the surface. At a distance from the stagnation point in the jet the flow is parallel to the surface, as it is also at points* A *and* B *of the cylinder. Figure* (c) *shows the variation of heat flow over the surface of the cylinder (after McAdam)*

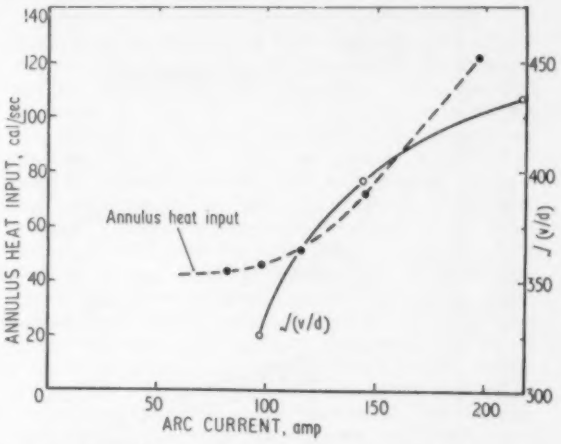
of the order of 0·3, so that the equations relevant to heat transfer to the annulus are:

$$Q = h \,.\, \Delta T$$

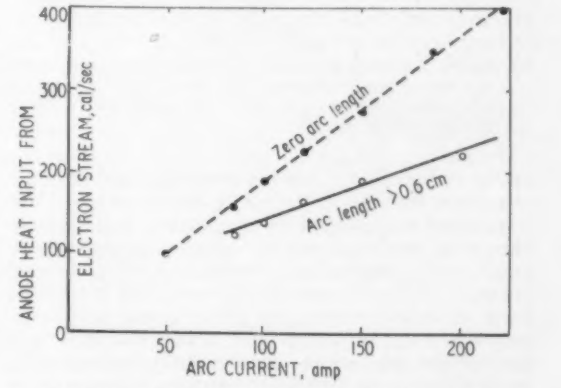
and

$$h = \frac{0{\cdot}3k}{d}\left(\frac{\eta C_p}{k}\right)^{\frac{1}{3}}\left(\frac{v\rho d}{\eta}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots \quad (6)$$

From Busz-Peuckert and Finkelnburg's measurements,[2] the mean temperature above the annulus, and thus $\Delta T$, for the argon arc was estimated as 13,000°C. while the surface of the copper anode was at a temperature not greater than 1,000°C., so that the mean boundary layer temperature was of the order of 7,000°C. Substituting the thermal constants corresponding to this temperature in equation (6), *i.e.*, $k = 2{\cdot}4 \times 10^{-3}$ cal/cm/sec/°C., $\eta = 2{\cdot}4 \times 10^{-3}$ c.g.s. units, $\rho = 5{\cdot}8 \times 10^{-5}$ g/cu.cm and $C_p = 0{\cdot}124$ cal/g/°C., the rate of heat transfer is found to be 288 cal/sec/sq.cm, which is about 2·4 times the experimentally determined value of 122 cal/sec/sq.cm. In view of the complexity of the conditions existing in the arc and of the approximations that have been necessary, this can be regarded as reasonable agreement. The formulation of the problem and data available are not adequate to explain the variation of heat transfer to the annulus with current. The simplest assumption that can be made is that when the heat transfer to the annulus becomes constant, *i.e.*, when the arc covers it completely, the temperature distribution is the same in every case. If this were so the rate of heat transfer would be proportional to $\sqrt{(v/d)}$ but as shown by the broken line in Fig. 18, this assumption leads to a decreasing upward trend of heat transfer with current, whereas the experimental results show an increasing upward trend. This could be accounted for, either by an increase in the temperature of the gas above the annulus, or by the fact that as the jet width increased, which it does with current, the magnitude of the constant should approach Woodrow's value.



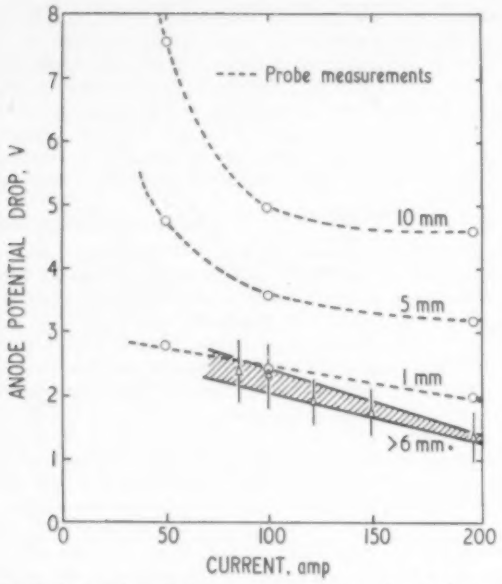

18—*Plasma jet heating to annulus as a function of current (derived from data in Fig. 16), and variation of* $\sqrt{(v/d)}$ *with current*




19—*Contributions of electron stream to heating of anode for arc lengths in excess of 6 mm, as a function of current. For comparison, heat input to anode obtained by extrapolating total anode heat input measurements to zero arc length (Fig. 3) is added*

#### Contribution of electron stream to heating of anode

The heat received by the central section of the three-part anode comprises the whole of the heat provided by the electron stream, together with some heat transfer from the plasma jet. It is possible to estimate the latter from the measurements of heat transfer to the annulus by making the assumption that for arc lengths above about 0·6 cm (at which the heat input to the annulus became constant) the plasma heating of the central section and the annulus was uniform, and thus arrive at the heat provided by the electron stream. It is clear from the last section that this estimate of the heat transfer from the jet can be only approximate, but since it is less than $\frac{1}{4}$ of the total heat received by the central section, this does not involve a serious error. When considering the 200-amp arc, for example, of the 320 cal/sec received by the central section about 75 cal were due to heat transfer from the plasma jet. Making a similar deduction from the heat input to the central section for all currents examined, the heat input due to the electron stream is found to vary with the current, as shown in Fig. 19. This is lower than the rate of heat input obtained by extrapolation to zero arc length of the total anode heating, given by Fig. 3*c*. It was shown in equation (1) that the heat received by the anode comprises the energy with which the electrons leave the arc column, plus that received on accelerating through the anode drop, together with their heat of condensation. Thus if a value can be ascribed to the work function for copper, and to the temperature of the arc column adjacent to the anode, the anode drop can be derived from the heat input measurements. Unfortunately neither of these factors are known very accurately for the conditions existing in the arc. The best value for the work function appears to be 4·3 eV. Adjacent to the anode the gas temperature varies from about 15,000°C. at the outer edge of the heat transfer boundary layer ($\sim 10^{-3}$ cm thick) to that of the metal at the surface. The anode drop takes place over a few electron mean free path lengths, *i.e.*, $10^{-5}$ cm, so that the electrons enter the anode drop with a temperature of, at the most, 5,000°C., for which $3kT/2e = 0{\cdot}65$ eV. Inserting these values in equation (1) the anode potential drop is found to have the values, and vary with current, as




20—*Variation of anode drop with current for arc lengths in excess of 6 mm, derived from heat input data in Fig. 19, compared with values obtained by probe measurements by Busz-Peuckert and Finkelnburg*[8]

shown in Fig. 20. In this figure are included the only other measurements of the anode drop in an arc of this type, which were made by Busz-Peuckert and Finkelnburg using probes. It can be seen that the two sets of results show similar trends with increasing current, but that the results obtained here are much lower than those of Busz-Peuckert and Finkelnburg, a discrepancy which was not unexpected, as they state that their method of measurement—the use of a cold probe in the arc to measure the electrical conditions at any point—leads to results which show changes in these conditions very well, but, due to the difficulty in estimating the contact potential between the cold probe and the hot plasma, the absolute value of the measurements is uncertain to within $\pm 2$ V, and therefore the disagreement between the two sets of results is not so wide as it at first seems. Busz-Peuckert and Finkelnburg also measured the heat input to the anode and obtained results with which the present work is in accord, so that the divergences in the anode potential drops derives either from the interpretation by the present authors using equation (1), or from the errors involved in probe measurements. In this connection it must be pointed out that for some conditions (*e.g.*, in the 20-amp arc, and for the arc lengths greater than 0·8 cm in the 40-amp arc) the probe measurements of Busz-Peuckert and Finkelnburg yield an anode drop which accounts for the whole of the heat input to the anode. If this is correct it refutes equation (1), which includes a contribution from the energy acquired by the electrons in the arc column and the energy of condensation.

#### Energy balances for the arc column

The analysis of heat transfer from a jet does not describe the conditions existing in the arc; these are only implicitly included in that the plasma jet velocity, diameter, and temperature are decided by the arc, and have to be measured experimentally. Clearly it is desirable that these should be determinable from first principles, but this involves the solution of three balance equations for the arc column. Since the primary function of the arc column is to maintain the passage of the current, a current balance equation has to be obeyed; this in turn requires that a region of conducting gas should be maintained at the necessary high temperature, so that an energy balance equation must be fulfilled. If there is a macroscopic gas flow, as in the type of arc with which the present work is concerned, then a mass balance equation must also be obeyed. The simultaneous solution of these three equations presents a theoretical problem of such magnitude that a solution is not likely in the foreseeable future, and the only arc for which the current, energy, and mass balances are known is the 200-amp carbon arc, for which the data was obtained as a result of numerous experimental measurements by Maecker and co-workers.[9] In these circumstances it is not therefore possible to analyse the measurements of energy consumption in the arc column made in the present work. The only comment that can be offered is that the thermal conductivity of the gas appears to be the most important factor, since it increases in the same order as the column gradient, but there is no simple relationship connecting the two; certainly the column gradient is not directly proportional to the thermal conductivity. In this connection it must be emphasized that it is the thermal conductivity at high temperatures that is important, and this is increased markedly by dissociation and ionization of the gas. (See for example the variation of thermal conductivity with temperature for nitrogen, determined by King[6] and reproduced in another paper in this series[1].)

#### Heat content of effluent gases

By comparing the heat carried away from the arc region, given by Fig. 5, with the energy dissipated in the arc column, it is found that the efficiency of heat transfer from the plasma jet for argon arcs was of the order of 55–75%, and for nitrogen arcs 75–90%. Since the total heat content of the gas after it had impinged on the anode was determined, whether it was transported to the walls of the chamber or extracted in the heat exchanger, the mean temperature of the gas jet leaving the anode plate can be calculated. The results are shown in Table II, which shows that the gas was still at a temperature of several thousand degrees centigrade with nitrogen temperatures generally lower than those of argon. The analysis of heat transfer from a jet is not sufficiently advanced to allow an interpretation of these results.

## Discussion

The initial aim of this work was to add to the fundamental knowledge of arc welding by examining the energy balance of an arc, and in particular to contrast the behaviour of a monatomic gas (argon) with that of diatomic gas (nitrogen). Data is presented for these arcs and for a limited number of measurements on helium and hydrogen arcs. The heating of

**Table II**

**Mean temperature of effluent gas from argon and nitrogen arcs**
Current range 50–350 amp

| *Arc Current, amp* | *Arc Length, cm* | *Gas* | *Heat carried away from Arc Region by Effluent Gases, cal/sec* | *Calculated Effluent Gas Temp.,* °K.* |
|---|---|---|---|---|
| 50 | 0·5 | Argon | 35 | 1000 |
| | | Nitrogen | 25 | 510 |
| | 1·0 | Argon | 40 | 1100 |
| | | Nitrogen | 40 | 820 |
| 100 | 0·5 | Argon | 35 | 1000 |
| | | Nitrogen | 30 | 610 |
| | 1·0 | Argon | 55 | 1550 |
| | | Nitrogen | 65 | 1325 |
| 185 | 0·5 | Argon | 40 | 1100 |
| | | Nitrogen | 40 | 820 |
| | 1·0 | Argon | 80 | 2250 |
| | | Nitrogen | 100 | 2050 |
| 275 | 0·5 | Argon | 110 | 3100 |
| | | Nitrogen | 60 | 1225 |
| | 1·0 | Argon | 190 | 5000 |
| | | Nitrogen | 140 | 2900 |
| 350 | 0·5 | Argon | 125 | 3450 |
| | | Nitrogen | 65 | 1325 |
| | 1·0 | Argon | 220 | 6150 |
| | | Nitrogen | 190 | 3900 |

* Assuming $C_p$=0·124 cal/g/°C. for argon
and $C_p$=0·235 cal/g/°C. for nitrogen

the cathode, and the electron stream contribution to the anode, do not change very much compared with the very marked variation of the energy dissipation in the arc column and the heat transfer from the column to the anode. The most important finding is the presence of the plasma jet, which Maecker predicted would arise wherever there is a constriction and a current density gradient in an arc. In the opinion of the authors, these jets will provide an understanding of many of the previously unexplained phenomena of arc welding. It has been shown in two other papers in this series that the jet determines the mechanism for metal transfer in consumable-electrode inert-gas shielded arc welding, and in the transport of the high-temperature reactive gases to the molten weld pool. The present work has demonstrated that the jet provides the means of heat transport from the arc column to the anode in non-consumable electrode welding, and provided that there is an adequate constriction at the consumable electrode the same should be true in this case. It is unfortunate that no measurements could be made of the characteristics of plasma jets in dissociable gases, owing to the intensity of their action, but it is probably this feature which is of value in deep-penetration welding. As the current is increased, the pressure exerted by the plasma jet increases, and causes the formation of a crater. King[10] has suggested that it is the contraction of the arc, which occurs when the ionization core forms in the argon arc at high current, with the associated increase in the intensity of the plasma jet, which brings about the deep penetration 'toe' in consumable-electrode argon-shielded welding. With dissociable gases the deep-penetration effect is further intensified by the liberation of the heat of reassociation at the bottom of the crater. A further phenomenon, in which the plasma jet may play an important part, is the entrainment of air in the argon shrouding atmosphere at high currents. The atmosphere of the arc is determined by the jet which sucks gas into the arc, and the composition of the gas that is sucked in. It would seem that in the current range 200–300 amp the gas shroud must provide an adequate inert atmosphere for the jet to entrain. At high currents air is also sucked in, as is shown by the 'puckering' phenomenon of the oxidation of aluminium welded at high currents, to overcome which extra secondary shielding has been found necessary.[11] The amount of gas which passes through the jet in the non-consumable electrode system investigated in the present work can be estimated from the measurements of jet diameter and velocity, and examples for a number of currents are presented in Table III, which shows that owing to the co-operative increase of jet diameter and velocity, the amount of gas flowing through the jet increases very rapidly with current and should approach the amount available in the shrouding gas stream, *i.e.*, 0·15 g/sec, in the region of 350–400 amp.

It is clear that one of the most interesting aspects requiring further investigation is the jet in dissociable gas systems, but it is very difficult to devise apparatus that does not disintegrate under the intensity of the jet action. The most profitable course is probably first to obtain information from the more amenable 'plasma projector' type of system, as described for example by Moss.[12] With a plasma projector the electron heating and the jet heating are separated, and in addition it is possible to commence with heat transfer at such a distance from the orifice, from which the jet originates, that no difficulty is involved, and then to decrease this distance as far as is practicable.

**Table III**

**Quantity of gas flowing through plasma jet in argon arcs at various currents**

| *Arc Current, amp* | *Plasma Jet Velocity, cm/sec* × $10^4$ | *Plasma Jet Dia., cm* | *Mass Flow Rate of Gas through Plasma Jet,* g/sec* × $10^{-2}$ |
|---|---|---|---|
| 100 | 2·2 | 0·15 | 1·3 |
| 150 | 4·9 | 0·23 | 6·5 |
| 225 | 8·7 | 0·34 | 26 |

* Calculated assuming that density of gas corresponds to temp. of 15,000°C.

It was pointed out in the introduction that the mechanisms of heat and mass transfer are similar in a system in which a plasma jet is present, in that in both cases cold gas is sucked into the arc and heated to form a high-temperature, high-velocity jet impinging on the anode. In heat transfer, the jet supplies heat to the anode, whereas in mass transfer the reactive gas combines with the molten metal. Salter and Milner[5] have applied a similar analysis to that used in the present paper, to mass transfer in the system titanium–argon–oxygen. Similar agreement is obtained in both cases, taking account of the fact that in mass transfer the concentration decreases with the distance from the edge of the jet and is difficult to assess, whereas in heat transfer the temperature decrease is more readily estimated. Thus, although much more evidence is

required, it would appear that the model postulated could profitably be pursued further.

There remains the problem of considering the present work in relation to actual welding systems, in that the presence of the molten pool might alter the significance of the results that have been obtained. Apps and Milner[13] investigated heat transfer in a non-consumable electrode system similar to that used in the present work, except that there was a molten pool present, thereby losing the advantages and accuracy of continuous flow calorimetry in favour of a closer approach to actuality. The results of these workers when compared with the present investigations show the same zero arc length heat input, but a lower rate of anode heating with increasing arc length. This would suggest that the electron heating is unaffected by the presence of the molten pool, but that heat transfer from the plasma jet is less, which is to be expected in view of the increased temperature of the anode. Thus the efficiency of heat transfer from the column of the argon arc, which was of the order of 55–75% in the present work, was somewhat less, varying from 45 to 65% in the work of Apps and Milner. A further result of their work was that although the heat input to the anode increased with arc length, the width of the weld bead remained constant, whereas isotherms further away from the source of heat were appreciably widened. They interpreted this result as meaning that the electron stream provided a highly localized, intense concentration of heat, which remained constant with arc length, but that as the arc length was increased a more diffuse source from the column, which did not contribute to the width of the fused zone, was superimposed on the electron source. The contribution to the formation of a molten weld bead made by the anode heating is important, and it is therefore of interest to correlate the observations on bead width with the present authors' measurements of the heat distribution to the anode. When using aluminium, for example, Apps and Milner worked mainly in the current range around 120 amp, where the zero arc length anode heat input (from Fig. 3*a*) was 240 cal/sec. When the arc length was increased to 0·5 cm no appreciable change in the weld bead width was obtained, despite the fact that Fig. 3*a* shows the heat input to have risen to 340 cal/sec. If, however, the arc length had been maintained as short as possible and the same heat input had been achieved by increasing the current, Apps and Milner's results show that the weld bead width would have doubled. From the heat inputs to the three-part anode (Fig. 16) it can be seen that at 120 amp increasing the arc length from near zero to 0·5 cm reduced the heat input to the centre section (dia. 6 mm), from 240 to 205 cal/sec, whereas the heat input to the annulus, with internal and external diameters 6 and 12 mm respectively, went from zero to 45 cal/sec, and the plate outside the annulus received the remaining 70 cal/sec. The width of the corresponding weld bead was 5 mm, *i.e.*, slightly less than the diameter of the central section. Thus, the concept of a concentrated central heat source with a more diffuse source superimposed on it is reasonable, and when determining the relationship between the energy arriving at the anode, and the formation of a molten zone, the use of a blanket figure for the efficiency of heat transfer is unsatisfactory, and it is necessary to take account of the multiple nature of the heat sources.

## Conclusions

(1) In an arc between a non-consumable tungsten cathode and a water-cooled copper anode in atmospheres of argon, nitrogen, helium, and hydrogen 80–90% of the energy expended in the arc goes to the anode.

(2) Heat flow to the anode comprises the heating of the electron stream and heat transfer from a high-velocity ($>10^4$ cm/sec), high-temperature plasma jet, which originates from the constriction of the current caused by the cathode spot.

(3) For argon arcs the heat transfer from the plasma jet can be interpreted in terms of a model of a high-temperature jet impinging on a plate, in which a conventional heat transfer analysis is applied.

(4) Measurements of the heat transfer from the plasma jet in dissociable gases were not possible because of the intensity of the jet action, and this fact suggests that such jets are responsible for the phenomenon of deep penetration welding.

## Acknowledgments

This work is part of a programme of research into some aspects of the joining of metals, which is being carried out at the Department of Industrial Metallurgy at the University of Birmingham. The authors wish to thank Professor E. C. Rollason, Head of the Department, for his interest and encouragement throughout the course of this work, and the Director of the United Kingdom Atomic Energy Authority at Harwell for financial support. They are also indebted to Dr. J. Woodrow of the Reactor Division at Harwell for informative discussions on heat and mass transfer and for his solution to the problem of a jet impinging on a plate, and to their colleague G. R. Salter for the stimulation that arises from constant discussions of problems of mutual interest.

## REFERENCES

1. D. R. Milner, G. R. Salter, and J. B. Wilkinson: *Brit. Welding J.*, 1960, vol. 7, p. 73 (this issue).
2. G. Busz-Peuckert and W. Finkelnburg: *Z. Physik*, 1954, vol. 139, p. 212, 1955, vol. 140, p. 540, 1956, vol. 144, p. 244, 1956, vol. 146, p. 655.
3. H. Maecker: *Z. Physik*, 1955, vol. 141, p. 204.
4. R. Wienecke: *Z. Physik*, 1955, vol. 143, p. 128.
5. G. R. Salter and D. R. Milner: *Brit. Welding J.*, 1960, vol. 7, p. 89 (this issue)
6. L. A. King: *Appl. Sci. Res.*, 1955–6, vol. 5B, p. 189.
7. J. A. Woodrow: Reactor Division, Harwell, Private Communication.
8. W. H. McAdam: 'Heat Transmission', McGraw Hill, 3rd edition.
9. H. Maecker: Private communication.
10. L. A. King: Private communication.
11. A. A. Smith and P. T. Houldcroft: *Brit. Welding J.*, 1958, vol. 5, p. 421.
12. A. R. Moss: Verbal presentation at Joining of Metals Conference, 1959 (see *Brit. Welding J.*, 1960, vol. 7, p. 71 (this issue) )
13. R. L. Apps and D. R. Milner: *British Welding J.*, 1955, vol. 2, p. 475.

*Welding*
# RESEARCH

B.W.R.A. REPORT

# Effect of Arsenic on Weldability and Notch Toughness of Mild Steel (To A.P.I. Grade *B* Specification)

*A literature survey and experimental work were undertaken by the British Welding Research Association and a British steel company to assess the influence of arsenic on the weldability and notch toughness of mild steel to A.P.I. Grade* B *specification.*

*The experimental evidence obtained suggests that arsenic up to and including 0·10% has no influence on weld crack susceptibility.*

*Assessment of tests of notch impact properties was complicated by the need to use laboratory melted heats, which were found to be of comparatively coarse grain: arsenic in excess of approximately 0·10% tended to raise the transition temperature of these steels, whereas Houdremont and also Kasatkin found no effect with arsenic up to approximately 0·25% in commercial steels (Bessemer and open-hearth with sulphur and phosphorus up to 0·055%).*

*In general, the evidence from all sources suggests that arsenic up to 0·10% will have no effect on fusion weld crack susceptibility, joint strength, or ductility, or on the notch toughness of the A.P.I. Grade* B *plate.*

*It should be noted that this arsenic content is two or three times that normally present in British steel; thus there is no evidence to support any suggestion that such steel is, for this reason, inferior to steels having lower arsenic contents.*

FOLLOWING certain suggestions in Canada that arsenic had a deleterious effect upon the weldability and notch toughness of mild steel to A.P.I. Grade *B* specification, experimental work was put in hand, and a literature survey was carried out.

Although the experimental work described in this document was limited to the study of the influence of arsenic on the metal-arc weldability and the notch toughness of this one grade of mild steel, a review of the literature dealing with the influence of arsenic on mechanical properties and weldability of mild steels in general was prepared.

The paper is divided into two parts, Part I being a survey of the literature, giving in considerable detail a resumé of certain published work and private communications; this part ends with conclusions drawn from these sources of information. Part II gives details of tests made specifically for this investigation by the British Welding Research Association and Stewarts & Lloyds Ltd., and a comparison is made between the experimental results and the published data.

## Part I—LITERATURE SURVEY

**Arsenic in Steel** (Bibliography No. 4 published by the Iron and Steel Institute[1])

(*a*) *Harbord and Tucker.*[2] Arsenic not exceeding 0·1% does not appear to affect bend ductility at room

Report RB/152/ALR/94B of the British Welding Research Association, received 26th November, 1959. 530

temperatures; above this value cold shortness appears and fully brittle material is produced at 1·0% arsenic. Forge weldability is reduced at 0·09% arsenic and forge welding becomes impossible at 0·35% arsenic.

(*b*) *Stead*.[3] Arsenic in the range 0·10–0·15% has no material effect on the mechanical properties of structural steel rolled from acid and basic Bessemer and open-hearth heats. At 0·20% arsenic, some reduction in bend ductility is noted, while at 1% arsenic tensile strength is increased and ductility, as judged by reduction in area, is materially reduced. Arsenic does not apparently tend to produce red shortness.

(*c*) *McKinney*.[4] Tests on converter steel were carried out to determine the effect of arsenic at levels of 0·1 and 0·5%. Forgeability was normal and the results did not indicate that arsenic has a detrimental effect on steel.

(*d*) *Cameron and Waterhouse*.[5] The mechanical properties and weldability of basic open-hearth steels at 0·5% carbon and 0·2%, 0·36%, and 0·46% arsenic were determined. At 0·2% arsenic, there was no apparent effect on the weldability but the impact properties, particularly in the hardened condition, were reduced. The effects of arsenic are similar to those of phosphorus but the quantity required to produce equivalent effects is very much greater.

(*e*) *Bauer*.[6] Arsenic is generally present in commercial iron and steel in amounts within the range 0·02–0·05%, larger amounts up to 1% being exceptional. The arsenic is present in solid solution. It segregates less than phosphorus but in the presence of the latter it is found with the phosphorus segregate. Arsenic in amounts less than about 0·05% has practically no influence on the static and dynamic properties of steel; in larger quantities it has a weakly adverse effect. Phosphorus and sulphur have a much stronger effect than arsenic but this is augmented by the simultaneous presence of arsenic.

(*f*) *Marchal*[7] found that forge weldability is seriously affected at 0·2% arsenic. Hahn,[8] dealing with a steel with 0·1% C, showed a limit of 0·1% arsenic for adequate weldability.

## Influence of Arsenic on Properties of Steel

(Houdremont, Bennek, and Neumeister[9])

**Tests on laboratory heats (0·15% C, unalloyed steel)**

(*a*) *Mechanical tests at room temperature*

In a very thorough programme of mechanical tests on steels with varying arsenic contents, the following conclusions were reached:

(i) Grain size is not affected up to 0·6% arsenic
(ii) Reduction in area is not affected up to 0·6% but is slightly lowered at 0·9% arsenic
(iii) Tensile strength shows a very slight increase as arsenic increases from 0·1 to 0·6%
(iv) Elongation and yield strength are unaltered up to 0·6% arsenic. Notch ductility in the normalized condition is unaltered up to 0·4% arsenic and is then reduced by 50% as arsenic increases up to 0·9%
(v) Notch ductility in the strain-aged condition is unaltered up to 0·4% arsenic and is then reduced gradually to about zero as arsenic increases to 0·9%.

(*b*) *Notch impact transition curves*

Tests on five steels. The position of the transition curves for steels with 0·04%, 0·12% and 0·14% arsenic in the normalized condition is virtually unaltered as arsenic increases, with a mid-point criterion at −40°C. Steels with 0·77% and 0·90% arsenic show a transition temperature above 40°C. using the same criterion.

In the strain-aged condition the steel with 0·04% arsenic shows a transition temperature of −50°C., that with 0·12% arsenic a transition at −20°C., and that with 0·24% arsenic one at 0°C., again using the mid-point criterion.

Aged by soaking for 8 hr at various temperatures after normalizing, arsenic contents at 0·04%, 0·16%, 0·38%, 0·77%, and 0·90% showed no change in notch toughness at temperatures up to 600°C. It was concluded from this series of tests that:

(i) Arsenic has no effect on the transition temperature of normalized mild steel up to, and including, a content of 0·24%, but at a content between 0·24 and 0·77% the temperature is raised
(ii) An increase in arsenic content from 0·04 to 0·12% raised the transition temperature in the strain aged condition
(iii) Arsenic has no effect on quench ageing.

(*c*) *Quenching*

Arsenic up to 0·6% has virtually no effect on the mechanical properties of low-carbon unalloyed steel water quenched from 820°C. (tensile, yield, reduction in area, elongation and notched impact). Tests on a Ni–Cr steel showed that arsenic above 0·4% reduced the ductility and increased the tensile strength of 3% Ni–Cr steel with 0·35% C, in the oil quenched and tempered condition.

**Tests on basic Bessemer steel (unkilled, 0·24% arsenic)**

(*a*) *Segregation and mechanical properties*

A thorough study was made of the segregation of arsenic in a large ingot and the following conclusions were reached:

(i) The highest arsenic content recorded was just below the top segregate
(ii) The lowest arsenic content recorded was in the skin, where it was found to be constant, this probably being due to vaporization
(iii) Only slight segregation was noted; for instance, from a melt value of 0·24% the content increased to 0·32% in the central axis.

Comparison was made with other segregating elements in this ingot. The greatest percentage variation from the mean value for carbon, sulphur, phosphorus and arsenic was:

| *C* | *S* | *P* | *As* |
|---|---|---|---|
| +112 | +204 | +97 | +67 |
| − 38 | − 54 | −41 | −33 |

These results clearly indicate that arsenic segregates to a lower degree than either carbon, phosphorus, or sulphur, and it should be noted that this is at a level of arsenic far higher than is ever encountered in normal commercial steel.

A similar ingot with 0·24% arsenic was processed to strip and to plates ($\frac{1}{2}$ in. thick) for comparison with basic Bessemer steel containing 0·02% arsenic. In this

comparison the steel containing 0·24% arsenic showed no change in yield, tensile, or elongation in plates rolled from the top and bottom of the ingot, tested in both the longitudinal and transverse directions. The notch impact transition temperature was determined for all these plates and there was no difference between those containing 0·02% arsenic and those containing 0·24% arsenic.

(*b*) *Weldability tests*

Weldability tests included hot crack susceptibility tests on 1·mm thick strip of basic Bessemer steel at 0·02 and 0·24% arsenic (top and bottom ingot positions). These showed that only a very slight effect could be detected when welded with or without added filler metal. Mechanical tests on butt welds, gas and electric arc, in the ½ in. thick plate material (again being taken from the top and bottom ingot positions) showed no effect on mechanical properties due to the increase in arsenic from 0·02% to 0·24%.

Forge weldability tests on 0·24% arsenic material showed severe loss of ductility, indicating a failure to produce a proper weld. On the other hand, flash butt welds in this material were completely satisfactory. Weldability tests were also done on Cr–Mo steel (1% Cr–0·25% Mo) sheets with arsenic at 0·02%, 0·15%, 0·24%, 0·55% and 1·24%. These tests were the same as those used for the basic Bessemer strip already referred to, being fusion tests for hot crack susceptibility with or without filler wire. There was no evidence of any change in crack susceptibility up to and including 0·24% arsenic. At 0·55% arsenic, weldability was still good in relation to arsenic-free electric steel and normal open-hearth steel with the usual arsenic content. The steel with 1·24% arsenic appeared to be strongly susceptible to hot cracking and would be considered unweldable.

The general conclusion from weldability tests is that the weldability of unalloyed and alloyed (Cr–Mo) material is not affected by arsenic up to about 0·25%, as far as can be judged by laboratory testing methods. Above 0·25% arsenic the weldability of gas welded sheets deteriorates. At 0·25% arsenic the strength properties of gas and arc welded plate are not affected and the flash weldability is satisfactory. The general inference from this very thorough examination of the effect of arsenic on the mechanical properties of welded joints and the fusion weldability of mild steel is that contents of arsenic exceeding 0·25% must be present before any effect can be observed.

**Table I**

**Chemical Composition of steels investigated by Kasatkin**

| *Serial No.* | *Heat No.* | *Thickness. mm* | *Composition, %* | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | *C* | *Mn* | *Si* | *S* | *P* | *As* |
| **Rimming Steels** | | | | | | | | |
| 1 | 6254 | 12 | 0·19 | 0·46 | Traces | 0·039 | 0·030 | 0·10 |
| 2 | 6254 | 20 | 0·19 | 0·46 | ,, | 0·039 | 0·030 | 0·10 |
| 3 | 4319 | 12 | 0·19 | 0·49 | ,, | 0·027 | 0·031 | 0·145 |
| 4 | 4319 | 20 | 0·19 | 0·48 | ,, | 0·026 | 0·032 | 0·145 |
| 5 | 9031 | 12 | 0·18 | 0·51 | ,, | 0·029 | 0·047 | 0·107 |
| 6 | 1310 | 20 | 0·17 | 0·56 | ,, | 0·036 | 0·056 | 0·12–0·16 |
| 7 | 1310 | 20 | 0·17 | 0·55 | ,, | 0·036 | 0·046 | 0·20 |
| 8 | 6331 | 20 | 0·18 | 0·63 | ,, | 0·040 | 0·034 | 0·23 |
| 9 | 6331 | 12 | 0·18 | 0·63 | ,, | 0·045 | 0·032 | 0·27 |
| 10 | 12609 | 12 | 0·19 | 0·43 | ,, | 0·030 | 0·016 | None |
| 11 | 12609 | 20 | 0·19 | 0·43 | ,, | 0·030 | 0·016 | None |
| **Killed Steels** | | | | | | | | |
| 12 | 10254 | 20 | 0·17 | 0·56 | 0·20 | 0·052 | 0·045 | 0·11 |
| 13 | 2366 | 12 | 0·18 | 0·56 | 0·21 | 0·026 | 0·032 | 0·15 |
| 14 | 2366 | 20 | 0·19 | 0·57 | 0·20 | 0·028 | 0·030 | 0·15 |
| 14A | 10251 | 20 | 0·16 | 0·38 | 0·17 | 0·036 | 0·030 | 0·22 |
| 15 | 9334 | 12 | 0·21 | 0·38 | 0·20 | 0·036 | 0·026 | 0·29 |
| 16 | 9334 | 20 | 0·16 | 0·37 | 0·18 | 0·036 | 0·030 | 0·28 |
| 17 | 11642 | 12 | 0·19 | 0·48 | 0·26 | 0·028 | 0·026 | None |
| 18 | 11642 | 20 | 0·19 | 0·48 | 0·26 | 0·028 | 0·026 | None |

## Permissible Arsenic Content in Open-Hearth Mild Steel (Kasatkin[10])

The effect of arsenic on the impact transition temperature of unwelded mild steel plate (open-hearth, killed and rimming grades) and its effect on the mechanical properties of submerged-arc welded joints, including notch impact properties in the heat-affected zone, were determined. The arsenic-bearing steels were made to levels of 0·10%, 0·15%, 0·20% and 0·25% arsenic. To determine the effect of arsenic in the presence of high sulphur and phosphorus, tests were also made on steels containing 0·04%–0·052% sulphur and up to 0·056% phosphorus with 0·20% carbon. The steels used are shown in Table I.

### Tests on unwelded plate

Mechanical tests, longitudinal and transverse to the rolling direction, showed that arsenic in the range 0·10–0·27% does not affect mechanical properties, even in the presence of 0·05% phosphorus or 0·05% sulphur. Impact tests were carried out in the longitudinal and transverse direction and the sensitivity of the steel to ageing after cold working was determined by heating for 1 hr at 250°C. after 10% extension.

It was found that arsenic up to 0·27% had no definite effect on the impact transition temperature of killed or rimming steels containing up to 0·05% sulphur and 0·05% phosphorus, nor did it appear to affect ageing characteristics, which were normal. Static tensile loading of a notched specimen at −183°C. suggested that when the arsenic content is greater than 0·27% it may reduce 'brittle strength'.

### Welded joints: Submerged-Arc welding with normal wire and powder

(*a*) *Hot cracking*

No effect on hot cracking in butt welds could be detected when welding the steel containing 0·27% arsenic and 0·045% sulphur.

(*b*) *Mechanical properties of welded joints*

Butt welded joints in steels 4, 6, 7, 9, 12, 14, 16 and 18 were machined to tensile and impact test bars. Arsenic up to 0·27% did not have any effect on transition temperature, ageing characteristics or on mechanical properties. Impact tests on the material in the heat-affected zone of steels 2, 4, 5, 7, 9, 14, 16 and 18 suggested that arsenic up to 0·27% does not have any effect on the transition temperature of the metal in this zone, nor does the impact strength decrease with the simultaneous presence of arsenic and high phosphorus (0·04–0·05%). Arsenic up to 0·27% does not affect the impact properties of the thermally aged zone in the heat-affected zone.

(*c*) *Mechanical properties of weldments in 20 mm plate*

Weldments were prepared to give longitudinal butt and fillet welds and were subjected to static tensile loading at 17°C. and −40°C. Some slight increase in strength and reduction in ductility with lowering of the testing temperature was noted in both killed and rimming qualities. Arsenic up to 0·2% did not appear to have any deleterious effect on the properties but the killed steel containing 0·28–0·29% arsenic showed a substantial lowering of ductility at −40°C.

The fillet weld specimens all fractured in the parent metal away from the welds, indicating that the steels with arsenic up to 0·27% were insensitive to the effect of stress concentration at 17°C. and at −40°C.

*Conclusions*

Arsenic contents up to 0·20% do not have any effect on the mechanical properties of rimming and killed steels (mild steel grade) made in the open-hearth furnace, even in the presence of up to 0·05% sulphur and phosphorus and up to 0·21% carbon, nor does arsenic up to 0·2% have any effect on the mechanical properties of weldments made in these steels. When arsenic exceeds 0·2% there is a tendency towards a reduction in 'brittle strength' of the steel and also in the ductility of weldments, so that an upper limit of 0·2% arsenic should be considered for mild steel made in the open-hearth furnace.

## Effect of Arsenic on Mechanical Properties of Welds in Mild Steel (Canonico and Schwartzbart[11])

The effect of arsenic on the bursting strength of small vessels fabricated from commercial welding fittings and on the notch impact properties and bursting strength of laboratory melted steels with various phosphorus levels was investigated. The steels were made to ASTM–A106 Grade *B* specification.

(*a*) *Bursting tests on vessels fabricated with commercial fittings*

The joints in the vessels were welded manually with E 6010 electrodes according to customary procedure; the fittings were 2·8 in. o.d. and 2·4 in. i.d.

All welds were radiographed and found to be sound. The vessels were hydrostatically tested to destruction, the results being given in Table II.

Evidently there was no significant difference in the strength of vessels made from low or high arsenic steel.

(*b*) *Bursting tests on vessels fabricated from laboratory heats*

Induction melted steels at 0·02%, 0·031%, 0·075%, 0·08%, 0·107% and 0·201% arsenic were processed to rounds, which were drilled to form pipes for fabrication into the same types of vessel as were used for the first series of bursting tests. The phosphorus content was around 0·010%. There was no significant difference between the bursting strengths of any of the vessels.

**Table II**

**Bursting tests of Canonico and Schwartzbart**

| *As*, % | *C*, % | *Mn*, % | *Si*, % | *P*, % | *S*, % | *Bursting Strength, lb/sq.in.* | | |
|---|---|---|---|---|---|---|---|---|
| 0·06 | 0·24 | 0·55 | 0·20 | 0·016 | 0·042 | 12500 | 13000 | 11700 |
| 0·003 | 0·22 | 0·69 | 0·22 | 0·004 | 0·03 | 13500 | 14000 | 14200 |
| 0·002 | 0·26 | 0·44 | 0·17 | 0·016 | 0·024 | 12200 | 12300 | 12200 |

**Table III**

**Steels tested for impact properties by Canonico and Schwartzbart**

| *As*, % | *P*, % | *C*, % |
|---|---|---|
| 0·02 | 0·009 | 0·19 |
| 0·031 | 0·009 | 0·18 |
| 0·075 | 0·011 | 0·20 |
| 0·080 | 0·009 | 0·20 |
| 0·107 | 0·009 | 0·20 |
| 0·201 | 0·012 | 0·19 |
| 0·032 | 0·054 | 0·14 |
| 0·074 | 0·059 | 0·14 |
| 0·092 | 0·065 | 0·14 |

(*c*) *Notch impact properties of the heat-affected zone*

Laboratory heats were forged to flats 5 in. wide × ⅝ in. thick and the Charpy V-notch was located in the heat-affected zone of a single run weld at the weld-metal/parent-metal interface.

The steels were as in Table III.

The relationships of temperature to energy absorbed and to percentage cleavage fracture were determined. The transition temperatures, based on different criteria, did not appear to be strongly linked to the arsenic content. Thus, using 50% of the maximum absorbed energy as a criterion, the highest transition temperature (70°F.) was obtained on a steel with 0·2% arsenic and 0·012% phosphorus, and the lowest (30°F.) on a steel with 0·032% arsenic and 0·054% phosphorus (carbon 0·14%). The steel with lowest arsenic and phosphorus had a transition temperature of 40°F. The steel with high arsenic and phosphorus (0·092% and 0·065% respectively) had a transition temperature of about 60°F.

On the basis of a 15 ft-lb energy criterion, the highest transition temperature (50°F.) occurred in the steel with 0·20% arsenic and 0·012% phosphorus and the lowest (−50°F.) in the steel with 0·031% arsenic and 0·009% phosphorus. The steel with the lowest arsenic and phosphorus had a transition temperature of 20°F., and that with the highest one of 0°F. On the basis of a 90% cleavage fracture criterion, a plot of transition temperature against arsenic content, including the low and high phosphorus steels, showed scatter but ignoring one steel and drawing the steepest possible line (giving the worst effect of arsenic) the slope suggested that 0·01% arsenic raises the transition temperature in the heat-affected zone by 2·7°F. When all the low phosphorus steels are included and the data examined by the method of least-squares, the increase in transition temperature per 0·01% arsenic is given as 1·9°F.

*Conclusions*

The room temperature hydrostatic bursting strength of fabricated vessels made from commercial low-arsenic steel (0·002% and 0·003% arsenic) is not greater than that of similar vessels made from commercial high-arsenic (0·06% arsenic) material. Arsenic contents up to 0·2% had no effect on the bursting

strength of vessels fabricated from laboratory melted steels. There did not appear to be any definite effect of arsenic on the Charpy V-notch impact transition temperature of the heat-affected zone except possibly a tendency towards raising the temperature for 90% cleavage fracture; there may be an increase of about 2°F. per 0·01% arsenic.

### Private Communications

(*a*) A study was made of the possible influence of arsenic within the range 0·011–0·087% on the notch impact transition temperature, after 3% and 5% strain and ageing, of semi-killed steels in the carbon range 0·06–0·25%. Phosphorus was present in the range 0·037–0·040% in all the higher arsenic steels. Material tested was plate for oil storage tanks. There was no evidence that arsenic up to and including 0·087% has any influence on transition temperature in the strain-aged condition.

(*b*) Experimental laboratory melted steels were prepared to determine the effect of arsenic up to 0·15% on the mechanical properties of steels at 0·12% and 0·35% carbon. Two levels of phosphorus were used, 0·02% and 0·04%. Arsenic levels of 0·03%, 0·05%, 0·07%, 0·10% and 0·15% were examined. There was no evidence that arsenic had any effect on tensile or impact properties, determined at room temperature, with either level of phosphorus.

(*c*) The arsenic contents of mild steel, ND I steel, and ND IV steel, which gave 15 ft-lb Charpy V-notch transition temperatures of +16°, −8° and −60°C. were found to be 0·027%, 0·051% and 0·030% respectively. The 75% crystallinity temperatures were +40°, +8° and −32°C. It is apparent that the ND I steel with a relatively high arsenic content has behaved, in regard to notch toughness characteristics, in a perfectly normal manner.

### Conclusions from Evidence in the Literature and from Private Communications

The experiments reported by Houdremont, Kasatkin and by Canonico cover Bessemer and open-hearth steels and also induction melted laboratory heats; furthermore, they include rimming and killed steels and the phosphorus and sulphur levels range up to 0·05%.

Their results are in agreement on the following points:

(*a*) Arsenic up to 0·24% has no effect on the notch impact transition temperature of the un-welded material in the as-rolled condition

(*b*) Arsenic up to 0·20% has no effect on fusion weldability assessed by the mechanical properties of butt welds, including oxyactetylene, metal-arc, and submerged-arc welding.

There is some uncertainty about the effect of arsenic on the notch impact properties of the heat-affected zone. Kasatkin reports no effect up to 0·27% arsenic on transition temperature, whereas Canonico reports a relationship between arsenic and transition temperature defined by the 90% cleavage fracture criterion. Canonico's results do not support any relationship between arsenic content and other transition temperature criteria so that it seems probable that arsenic has little effect on the notch impact properties of the heat-affected zone, at least up to a content of 0·2%.

Kasatkin shows that there is a tendency towards reduction of ductility in weldments tested under static loading at low temperatures (−40°C.) when the arsenic content reaches 0·27%, and suggests a limit of 0·2% arsenic.

Some uncertainty also exists in regard to the effect of arsenic on strain-age embrittlement. The results reported in the literature taken together confirm that arsenic below 0·087% has no effect; above this value Houdremont reported that arsenic raises the transition temperature in the strain aged condition, but Kasatkin found it to have no effect up to 0·27%, the behaviour of rimming and killed steels being normal. Houdremont's steels were laboratory melts and it may not be advisable to expect direct agreement with the open-hearth steels used by Kasatkin.

It is concluded that arsenic up to 0·2% in the parent plate will have no effect on the strength and ductility of fusion welded joints in open-hearth rimming and killed steels with normal sulphur and phosphorus levels, nor will it have any significant effect on the notch toughness characteristics of the parent metal or the weld joint.

## Part II—TESTS TO DETERMINE EFFECT OF ARSENIC ON WELDABILITY AND MECHANICAL PROPERTIES OF MILD STEEL

These tests were arranged to study the influence of arsenic on the weld-metal crack susceptibility using one type of coated electrode, and to determine its effect on the notch toughness characteristics of the steel. They were carried out by Stewarts & Lloyds Ltd. and the British Welding Research Association using 40 lb laboratory melts to A.P.I. Grade *B* analysis (nominally 0·2% carbon, Si-killed steel) with arsenic contents varying from 0·003% up to and including 1·26%.

The composition of the steels and weld metals examined is given in Table IV.

The effect of arsenic on the following properties was determined:

(i) Weldability, *i.e.*, susceptibility to weld-metal cracking in the Reeve Fillet Weld Test, the B.W.R.A. Controlled Thermal Severity Test, the Houldcroft Fishbone Test and the Murex Hot Cracking Test
(ii) Rate of work hardening
(iii) Amount of strain ageing after work hardening
(iv) Impact properties. Transition curves as normalized and after straining and ageing
(v) Quench ageing.

### Effect of Arsenic on Weldability

#### Reeve Fillet Weld Test

This test assesses resistance to cold and hot cracking under conditions of severe restraint; two plates,

**Table IV**

**Analysis of steels and weld metal used by B.W.R.A.**

| *Cast No.* | 1428 | 1391 | 1381 | 1382 | 1407 | 1397 | 1403 | 1441 | 1405 | 1406 | *All-weld Metal* 6 s.w.g. | *All-weld Metal* 10 s.w.g. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C, % | 0·175 | 0·192 | 0·170 | 0·186 | 0·180 | 0·163 | 0·19 | 0·19 | 0·17 | 0·17 | — | — |
| Mn, % | 0·44 | 0·695 | 0·50 | 0·58 | 0·44 | 0·43 | 0·42 | 0·54 | 0·41 | 0·43 | — | — |
| Si, % | 0·12 | 0·225 | 0·20 | 0·22 | 0·08 | 0·10 | 0·125 | 0·15 | 0·103 | 0·125 | — | — |
| S, % | 0·028 | 0·017 | 0·016 | 0·027 | 0·022 | 0·022 | 0·023 | 0·021 | 0·020 | 0·024 | 0·034 | 0·027 |
| P, % | 0·023 | 0·030 | 0·011 | 0·019 | 0·018 | 0·018 | 0·019 | 0·020 | 0·020 | 0·024 | 0·028 | 0·021 |
| As, % | 0·003 | 0·006 | 0·022 | 0·033 | 0·032 | 0·081 | 0·108 | 0·294 | 0·576 | 1·26 | 0·046 | 0·033 |

**Table V**

**Reeve Fillet Weld Test**

½ in. thick plate. No preheat. Electrodes to A.W.S. E7010 Specification

| *Cast No.* | *Analysis, % Plate* S | P | As | *Weld Bead* S | P | As | *Electrode Gauge, s.w.g.* | *Dilution by Parent Plate, %* | *Crack Length, in.* In Weld Metal* A | B | C | *In Parent Metal* A | B | C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1407 | 0·022 | 0·018 | 0·032 | 0·025 | 0·023 | 0·033 | 6 | — | Nil | Nil | Nil | Nil | Nil | Nil |
| | | | | — | — | 0·043 | 10 | — | Nil | Nil | Nil | Nil | Nil | Nil |
| 1397 | 0·022 | 0·018 | 0·081 | 0·025 | 0·022 | 0·046 | 6 | — | Nil | Nil | Nil | Nil | Nil | Nil |
| | | | | — | — | 0·055 | 10 | — | Nil | Nil | Nil | Nil | Nil | Nil |
| 1441 | 0·021 | 0·020 | 0·294 | 0·029 | 0·019 | 0·120 | 6 | 29 | Nil | Nil | Nil | Nil | Nil | Nil |
| | | | | — | — | 0·120 | 10 | 33 | Nil | Nil | Nil | Nil | Nil | Nil |
| 1405 | 0·020 | 0·020 | 0·576 | 0·024 | 0·024 | 0·220 | 6 | 33 | Nil | Nil | Nil | Nil | Nil | Nil |
| | | | | 0·030 | 0·026 | 0·160 | 10 | 22 | Nil | Nil | 0·05 | Nil | Nil | Nil |
| 1406 | 0·024 | 0·024 | 1·26 | 0·026 | 0·023 | 0·528 | 6 | 40 | 0·024 | Nil | Nil | Nil | Nil | Nil |
| | | | | 0·030 | 0·026 | 0·522 | 10 | 40 | 0·008 | 0·015 | 0·005 | Nil | Nil | Nil |

* All cracks occurred at the root.

All weld-metal deposit analysis:

| | *P*, % | *S*, % | *As*, % |
|---|---|---|---|
| 6 s.w.g. | 0·028 | 0·034 | 0·046 |
| 10 s.w.g. | 0·021 | 0·027 | 0·033 |

which are bolted to a heavy backing plate and prevented from moving laterally by anchoring welds, are fillet welded together by the test electrode.[12]

(*a*) *Test Data*

Plate: ½ in. thick, normalized, ground surfaces and machined edges, no pre-heat.

Electrodes: Commercial high-tensile ½% Mo to A.W.S. E 7010 and BS.1719: 1951 E110P specifications. These electrodes are commonly used for 'stove-pipe' welding in Canada.

Incubation: A standing period, for crack development, of 24 hr bolted, and one week unbolted, was allowed before sectioning.

Examination: Sections *A*, *B* and *C* taken at 1½ in. from start, at centre, and at 1½ in. from finish of weld respectively, were examined microscopically at ×200 magnification after etching in nital.

A hardness survey was carried out on the centre sections *B*.

(*b*) *Test Results*

The cracking assessment results are given in Table V, and hardness survey results in Table VI. The type of cracking is illustrated in Fig. 1, this being a section from the steel with 0·57% arsenic. It should be noted that this was the specimen showing the longest crack, but was the only one to show cracking in a weld made on the steel containing 0·57% arsenic.

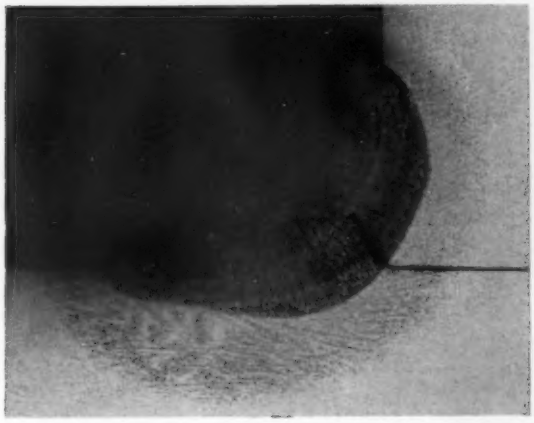
(*c*) *Conclusions*

There is no evidence of weld cracking until the arsenic content of the plate reaches 0·57%, and then only one section out of six examined shows a crack. At 1·2% arsenic in the plate, four sections out of six are cracked. It is inferred that an arsenic content in the plate greater than 0·5% promotes root cracking under

**Table VI**

**Hardness Surveys on Reeve Test Specimens**

| *Cast No.* | *Arsenic in Plate, %* | *Parent Plate* | *Hardness, $HD_{30}$ Heat-Affected Zone* 6 s.w.g. Electrodes | *Heat-Affected Zone* 10 s.w.g. Electrodes | *Weld Deposit* 6 s.w.g Electrodes | *Weld Deposit* 10 s.w.g. Electrodes |
|---|---|---|---|---|---|---|
| 1407 | 0·032 | 132–145 | 160–190 | 183–229 | 206–227 | 268–308 |
| 1397 | 0·081 | 139–157 | 164–193 | 173–219 | 225–244 | 241–289 |
| 1441 | 0·294 | 145–158 | 169–210 | 200–241 | 219–225 | 274–303 |
| 1405 | 0·576 | 145–168 | 164–206 | 189–210 | 198–246 | 267–309 |
| 1406 | 1·26 | 153–181 | 180–212 | 201–218 | 201–229 | 262–283 |



1—*Cracking in fillet weld in Reeve Test on steel containing 0·576% arsenic* ×8

the conditions of the Reeve Fillet Weld Test but a lower content has no effect on cracking. Analysis of the actual weld beads suggests that the arsenic content of the bead must exceed 0·20% before cracking is likely to occur.

Arsenic has no effect on the hardness of the weld metal or heat-affected zone, within the range tested.

**B.W.R.A. Controlled Thermal Severity Test**

This test determines the influence of cooling rate on cracking under restraint.[13]

(*a*) *Test Data*

Plate: ½ in. thick, normalized, machined surfaces and edges, no pre-heat.
Electrodes: As for Reeve Test.
Incubation: As for Reeve Test.
Examination: As for Reeve test but no hardness test.

(*b*) *Test Results*

The cracking assessments are given in Table VII.

(*c*) *Conclusions*

The small change in weld cooling rate brought about by the change in thermal severity number from 4 to 6 has little or no influence on the incidence or extent of cracking. As in the Reeve test there is no evidence of weld-metal cracking until the arsenic content of the plate reaches 0·57% and then only one section out of twelve examined shows a crack. At 1·26% arsenic in the plate, seven sections out of twelve examined show cracks. It may be inferred that an arsenic level in the plate greater than 0·5% promotes root cracking in welds made with this particular electrode. This confirms the evidence of the Reeve Test. The arsenic content of the weld beads is generally higher than that recorded for weld beads deposited in the Reeve Test on the same plate material, indicating a generally deeper penetration in the B.W.R.A. Tests. The lengths of the cracks are less than in the Reeve Test, this being explained by the lower rigidity of the C.T.S. Test.

**Houldcroft Fishbone Test**

This test assesses the comparative hot crack susceptibility of weld metal by imposing strain on the metal as it cools from the liquid state. The test was developed originally for use on light alloys.[14]

(*a*) *Test Data*

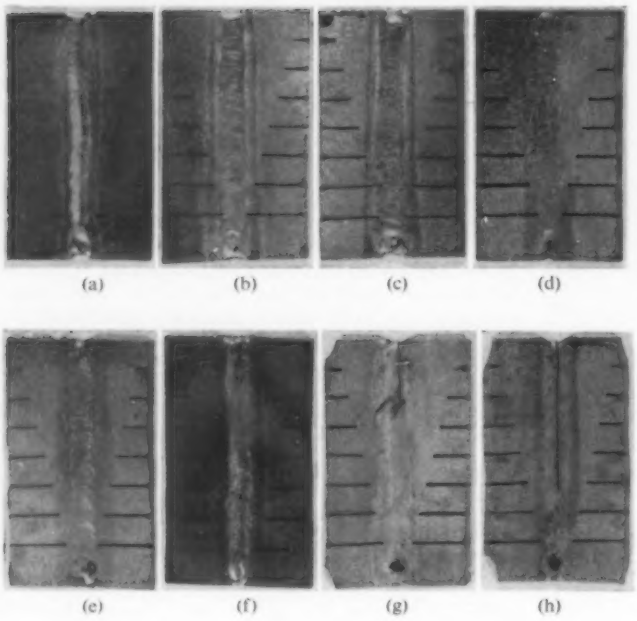
Plate: ⅛ in. thick, normalized.
Dimensions: 4½ × 2¾ in. with 7 saw cuts on each side (see Fig. 2).
Procedure: The specimen is placed on a carbon block, and an argonarc (tungsten electrode) torch is traversed along the mid-section at a current level and forward speed which just permit full penetration. A crack initiated at the edge may be propagated until the decreasing restraint due to the lengthening cuts imposes insufficient strain.
Interpretation: The Fishbone Test is purely comparative; for direct use there must be a background of practical experience to establish the relationships between cracking in the test under specific conditions of material thickness, specimen dimensions, current, etc., and cracking

**Table VII**

**Controlled Thermal Severity Tests: Fillet Welds**

½ in. thick plate. No preheat. Electrodes to A.W.S. E7010 Specification

| *Cast No.* | *Plate As* | *Analysis, % Welds* *As* | *S* | *P* | *Electrode Gauge, s.w.g.* | *Energy, kj/in.* | *Speed, in./min* | *Leg Lengths* *V* | *H* | *Thermal Severity Number* | *Dilution, %* | *Lengths of root cracks, in.* *A* | *B* | *C* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1407 | 0·032 | — | — | — | 8 | — | 7·5 | 0·23 | 0·26 | 4 | | Nil | Nil | Nil |
| | | — | — | — | 6 | — | 7·8 | 0·27 | 0·33 | 4 | | Nil | Nil | Nil |
| | | 0·042 | — | — | 8 | 36 | 6·2 | 0·23 | 0·28 | 6 | | Nil | Nil | Nil |
| | | 0·037 | 0·024 | — | 6 | 52 | 6·7 | 0·30 | 0·33 | 6 | 60 | Nil | Nil | Nil |
| 1403 | 0·108 | — | — | — | 8 | 34 | 6·5 | 0·27 | 0·25 | 4 | | Nil | Nil | Nil |
| | | — | — | — | 6 | 40 | 7·8 | 0·27 | 0·34 | 4 | | Nil | Nil | Nil |
| | | 0·082 | 0·021 | — | 8 | 33 | 7·2 | 0·20 | 0·22 | 6 | | Nil | Nil | Nil |
| | | 0·100 | 0·022 | — | 6 | 50 | 8·2 | 0·27 | 0·37 | 6 | 87 | Nil | Nil | Nil |
| 1405 | 0·576 | — | — | — | 8 | — | 6·8 | 0·25 | 0·26 | 4 | | Nil | Nil | Nil |
| | | — | — | — | 6 | 40 | 8·6 | 0·26 | 0·33 | 4 | | Nil | Nil | Nil |
| | | 0·348 | 0·022 | 0·019 | 8 | 35 | 6·6 | 0·23 | 0·23 | 6 | | Nil | Nil | Nil |
| | | 0·466 | 0·023 | 0·026 | 6 | 51 | 7·2 | 0·28 | 0·35 | 6 | 79 | Nil | 0·0005 | Nil |
| 1406 | 1·26 | 0·733 | 0·022 | 0·019 | 8 | 33 | 5·8 | 0·29 | 0·26 | 4 | | Nil | 0·0013 | 0·009 |
| | | 0·79 | 0·024 | 0·025 | 6 | 43 | 8·2 | 0·28 | 0·33 | 4 | | 0·0022 | 0·0025 | Nil |
| | | 0·733 | 0·022 | 0·019 | 8 | 38 | 6·2 | 0·23 | 0·25 | 6 | | Nil | Nil | Nil |
| | | 0·80 | 0·025 | 0·025 | 6 | 44 | 6·7 | 0·26 | 0·34 | 6 | 62 | 0·0019 | 0·0033 | Nil |




2—*Photograph of Fishbone test pieces, showing amount of cracking in different steels:*

(*a*) H.F.1428, 0·003% As;
(*b*) H.F.1381, 0·022% As;
(*c*) H.F.1382, 0·033% As;
(*d*) H.F.1397, 0·081% As;
(*e*) H.F.1403, 0·108% As;
(*f*) H.F.1441, 0·294% As;
(*g*) H.F.1405, 0·576% As;
(*h*) H.F.1406, 1·26% As

**Table VIII**

**Houldcroft Fishbone Test**

| *Cast No.* | *Arsenic, %* | *Lengths of Cracks, in.* | *Comments* |
|---|---|---|---|
| 1381 | 0·022 | nil | |
| 1382 | 0·033 | nil | |
| 1397 | 0·081 | 0·25 | Crack initiated but not propagated |
| 1403 | 0·108 | 0·22 | Crack initiated but not propagated |
| 1441 | 0·294 | 0·86 | Crack initiated and propagated |
| 1405 | 0·576 | 0·97 | Crack initiated and propagated |
| 1406 | 1·26 | 2·72 | Crack initiated and propagated |

experience under general practical conditions. These data are not yet available for steel but the test results reported here show the small influence of arsenic on hot cracking.

(*b*) *Results*

The results are given in Table VIII and illustrated in Fig. 2.

(*c*) *Conclusions*

Under the particular conditions (dimensions of test specimens, etc.) of these experiments, there is insufficient restraint to initiate a crack when the arsenic content is at or less than 0·033%. At 0·081% and 0·108% arsenic the restraint is insufficient to propagate a crack already initiated. At 0·29% arsenic the restraint is sufficient to propagate the initiated crack and the results obtained at the higher arsenic levels show that as arsenic increases beyond 0·29% the restraint required for propagation decreases, indicating that arsenic at very high levels promotes hot crack susceptibility.

**Murex Hot Cracking Test**

The principle of this test is to compare hot-crack susceptibility of welds under controlled conditions of straining at and below solidification temperature. A fillet weld is laid between plates held edge-on in rigid clamps, one of which is rotated away from the other to open out the weld, rotation beginning five seconds after the arc is struck.[15] Increasing rotational speed increases the test severity at a given weld size.

(*a*) *Test Data*

Plate: ½ in. thick.

Electrodes: As for previous tests: 8 s.w.g. electrode baked 1 hr at 150°C., 6 s.w.g electrodes used 'as received'.

Conditions: The rotational speeds (machine speed) for each electrode gauge were selected to give approximately equal conditions of test severity throughout the tests.

Interpretation: Cracks less than 0·5 in. long are disregarded, being formed before rotation begins. Their cause and significance is not clear. The results are here assessed on a crack/no-crack basis under selected straining conditions

(*b*) *Test Results*

Reported in Table IX.

(*c*) *Conclusions*

When the arsenic content of the plate is equal to or less than 0·108%, the crack length is less than 0·5 in., and is therefore not significant (see results above the line in Table IX); when the arsenic content in the plate is equal to or greater than 0·294% the crack length reaches or exceeds 0·5 in. It is concluded that weld-metal hot cracking is not promoted, under the specific testing conditions used in these experiments, until the arsenic content of the plate exceeds 0·108%. A crack

**Table IX—Murex Hot Cracking Test**

½ in. thick plate. Electrodes to A.W.S. E7010 Specification

| Cast No. | Parent Metal Analysis, % S | P | As | Weld Bead Analysis, % S | P | As | Electrode Gauge, s.w.g. | Dilution,* % (approx.) | Machine Speed No. | Length of Crack, in. | Average Crack Length for Both Gauges, in. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1428 | 0·028 | 0·023 | 0·003 | 0·022 | 0·024 | 0·021 | 6 | 58 | 7 | Nil | Nil |
| | | | | | | | 6 | | 7 | Nil | |
| | | | | | | | 8 | | 6 | Nil | |
| | | | | | | | 8 | | 6 | Nil | |
| 1407 | 0·022 | 0·018 | 0·032 | 0·022 | 0·021 | 0·042 | 6 | 50 | 7 | Nil | 0·04 |
| | | | | | | | 6 | | 7 | Nil | |
| | | | | | | | 8 | | 6 | Nil | |
| | | | | | | | 8 | | 6 | 0·14 | |
| 1403 | 0·023 | 0·019 | 0·108 | 0·021 | 0·020 | 0·078 | 6 | 52 | 7 | Nil | 0·07 |
| | | | | | | | 6 | | 7 | 0·3 | |
| | | | | | | | 8 | | 6 | Nil | |
| 1441 | 0·021 | 0·020 | 0·294 | — | — | 0·17 | 6 | 50 | 7 | 1·8 | 2·3 |
| | | | | | | | 6 | | 7 | 2·2 | |
| | | | | | | | 6 | | 7 | 3·0 | |
| 1405 | 0·020 | 0·022 | 0·576 | 0·021 | 0·022 | 0·339 | 6 | 55 | 7 | 0·6 | 0·50 |
| | | | | | | | 6 | | 7 | 1·0 | |
| | | | | | | | 8 | | 6 | Nil | |
| | | | | | | | 8 | | 6 | 0·5 | |
| 1406 | 0·024 | 0·024 | 1·26 | 0·023 | 0·023 | 0·559 | 6 | 43 | 7 | 1·3 | 0·45 |
| | | | | | | | 6 | | 7 | Nil | |
| | | | | | | | 8 | | 6 | 0·5 | |
| | | | | | | | 8 | | 6 | Nil | |

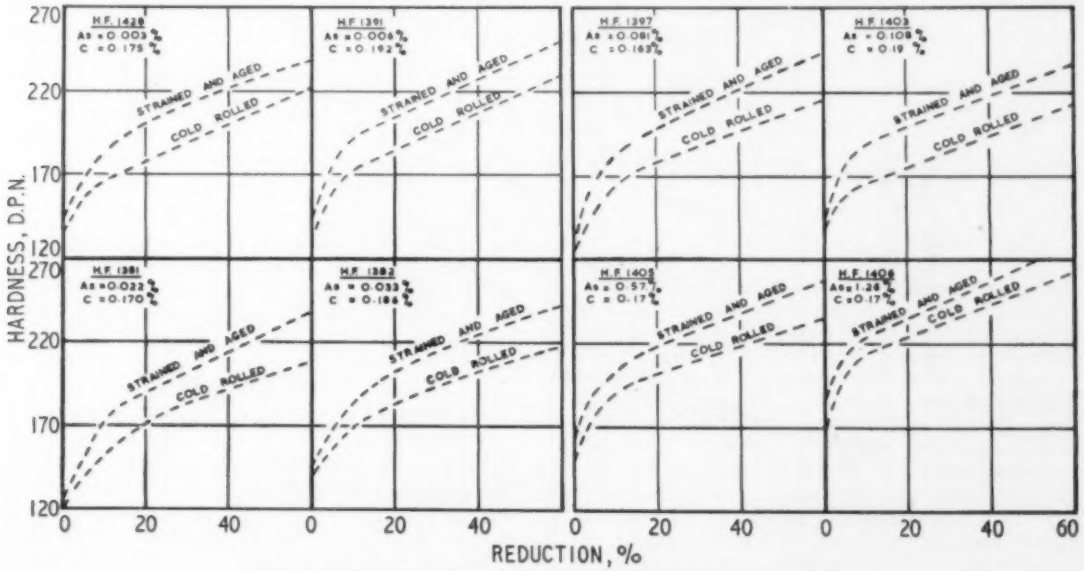
* Calculated from As content. In undiluted weld metal As = 0·046%

length not exceeding 0·5 in. under these testing conditions indicates that the particular combination of electrodes and parent plate would be free from cracking under practical production conditions involving severe restraint, and would be suitable for very heavy work in plate over 1½ in. thick, such as superheater headers, boiler-tube plate, high-pressure vessels, thick-walled pipes, etc. (see ref. 15, p. 446). The results suggest that the arsenic content of the parent plate must exceed 0·1% before any effect on weld metal hot cracking of A.W.S. Class E 7010 electrodes could be anticipated, even under the most severe conditions of restraint.

## Effect of Arsenic on Mechanical Properties

### Work hardening

Work hardening curves for the different steels are shown in Fig. 3. The initial hardness of the normalized test pieces remains unchanged as arsenic increases up to 0·57%; above this level the initial hardness increases with increasing arsenic content. However, the extreme range of initial hardness covered is not more than 50 D.P.N., (*i.e.*, 120 to 170). The rate of increase of hardness with percentage reduction is substantially the same over the range of arsenic contents examined.




3—*Effect of arsenic on 0·2% carbon steel. Cold rolling and ageing curves*

**Table X**

**Low and Gensamer Strain Ageing Test**

| *Cast No.* | *Arsenic Content of Steel, %* | *Low and Gensamer Index* |
|---|---|---|
| 1428 | 0·003 | 21·6 |
| 1391 | 0·006 | 18·2 |
| 1381 | 0·022 | 23·5 |
| 1382 | 0·033 | 23·4 |
| 1403 | 0·108 | 22·0 |
| 1405 | 0·576 | 19·2 |
| 1406 | 1·26 | 18·8 |

For example, at 60% reduction the steel containing 0·006% arsenic showed an increase in hardness of 93 D.P.N. and that containing 1·26% arsenic an increase in hardness of 106 D.P.N. for the same percentage reduction.

#### Strain ageing

The effect of arsenic on strain-ageing characteristics is also shown in Fig. 3. Ageing was carried out for 1 hr at 200°C. after the indicated amounts of cold work. It will be noted that the increase in hardness due to ageing is constant over the range 0·003–0·57% arsenic; it is slightly less at 1·2%. The Low and Gensamer Test was carried out on steels with arsenic contents up to 1·26%. The results are given in Table X. There is no marked variation in the strain-ageing index with increasing arsenic contents. It is concluded that arsenic up to and including 1·2% does not affect strain-ageing characteristics of normalized 0·2% carbon steel.

#### Impact transition temperatures

The effect of arsenic on the impact properties in the normalized and in the strain-aged condition was studied. It should be emphasized that the steels used were produced as small heats (40 lb) in a laboratory furnace and were coarse grained. The transition temperatures are therefore higher than those normally recorded on similar steel processed from commercial ingots, and should not be regarded as representative of the commercial product. Purely on a comparative basis the transition curves shown in Figs. 4 and 5 indicate the effect of arsenic on the notch-toughness/temperature relationship of coarse grained Si-killed steel in the normalized and in the strain-aged conditions respectively.

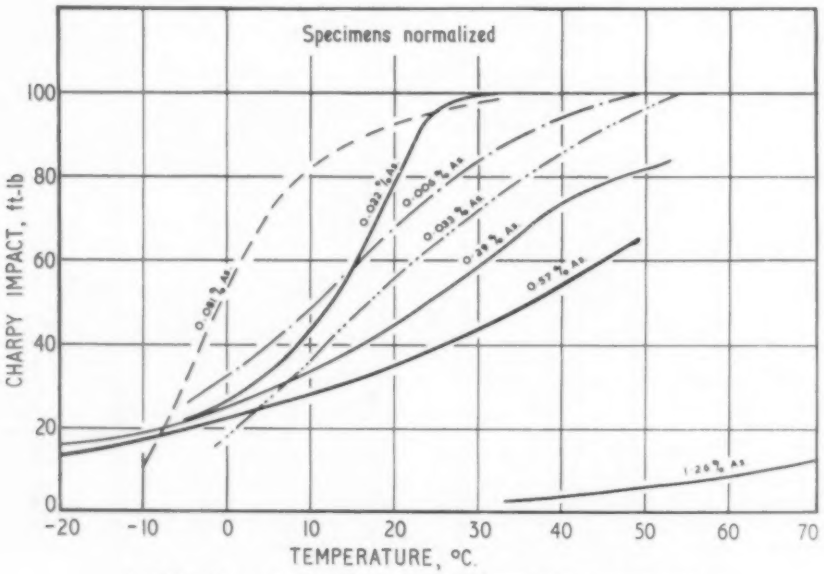
It will be noted from Fig. 4 that as arsenic increases from 0·006% up to and including 0·081% no particular trend is observed; at 0·29% a rise in transition temperature is apparent and this increases at 0·57% and 1·26% arsenic. Thus it is inferred that arsenic has no effect on the transition temperature of normalized 0·2% carbon steel until a content exceeding 0·08% is reached. At 0·29% or above, increasing arsenic promotes higher transition temperatures.

After straining and ageing (see Fig. 6) the steels with 0·29% or more arsenic show a greater drop in impact properties than those with lower arsenic contents.

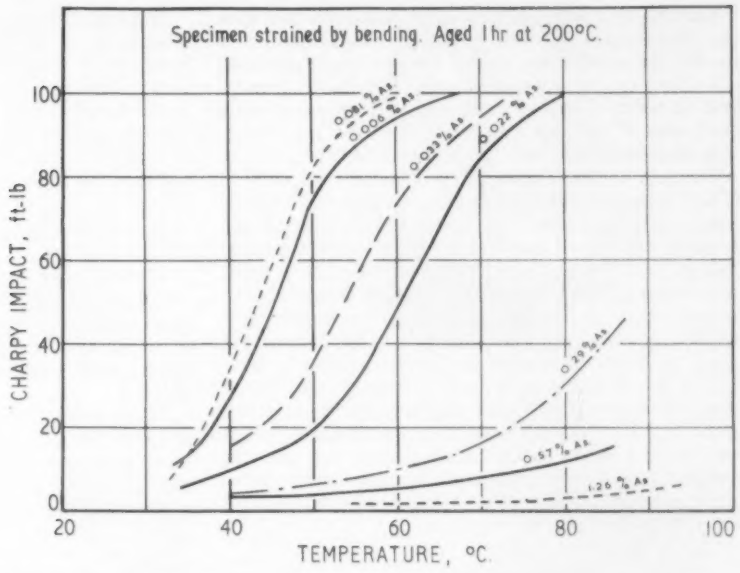
It is evident that the impact properties of coarse grained Si-killed steel are unaffected by arsenic, either in the normalized or strain-aged conditions, until the arsenic content exceeds 0·08%.

#### Quench ageing

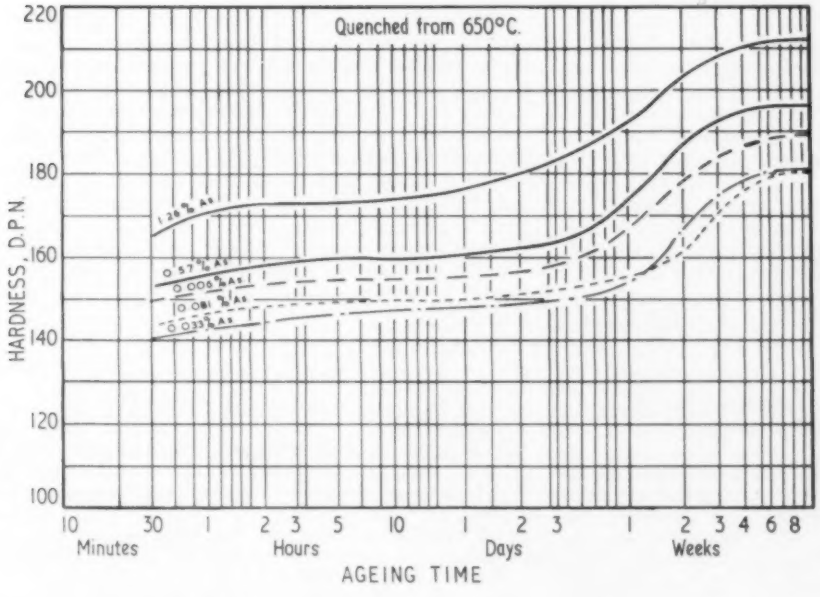
Figure 6 shows the increase in hardness on ageing after air cooling from 950° to 650°C. followed by water quenching. The initial hardness after quenching increases with increasing arsenic content. The rise in hardness on ageing up to 10 weeks is very similar on all the steels examined. The rather high initial hardness




*4—Effect of arsenic on 0·2% carbon steel. Charpy V-notch impact tests*




*5—Effect of arsenic on 0·2% carbon steel. Charpy V-notch impact tests*




*6—Effect of arsenic on 0·2% carbon steel. Quench ageing*

of the steel containing 0·006% arsenic is due to its slightly higher carbon and manganese contents.

## DISCUSSION

### Weldability Tests

The electrodes selected for the experimental work are of a type commonly used for pipe welding and have deep-penetration characteristics. This is confirmed by the calculated dilution in the tests, ranging approximately from 30 to 75% according to conditions nd operator. Such electrodes will pick up substantially more arsenic than those of a type producing less penetration so that the selected combination of electrode and plate represents the worst conditions of arsenic pick-up likely to be met in practice. The Reeve Test and Controlled Thermal Severity Test require welds to be made under conditions of restraint which may be described as extremely and moderately severe respectively. The 'hot cracking' laboratory test (Murex and Fishbone) need to be linked with practical experience; the conditions selected represent the worst met in practical welding on structural steels.

The arsenic content of the undiluted weld metal from the 6 s.w.g. electrodes at 0·046% is higher than the normal level.

Bearing the above facts in mind it may be said that any conclusions reached regarding the influence of arsenic on weldability based on the work reported will apply to the worst conditions met in the general field of welding. More particularly, deep-penetrating electrodes of the type examined are used less widely than electrodes with half the penetration power.

The results show that when welding with A.W.S. E 7010 type electrodes the influence of arsenic on weld metal cracking in the Reeve and C.T.S. Tests is not detected until the content in the plate reaches a value between 0·576 and 1·26%, corresponding to a value in the weld metal exceeding 0·2%. It is recognized that, in respect to conditions promoting hot cracking in welds, the restrained fillet weld test of the Reeve type is not as severe as certain conditions arising in practice in the welding of circular joints in very heavy plate; the Murex Hot Crack Test, as carried out in this investigation, links up with these particularly severe conditions and the results obtained indicate that the arsenic content of the plate must reach a level between 0·108 and 0·29% before any effect on hot cracking could be expected.

### Mechanical Properties

Arsenic up to 1·2% appears to have no effect on work hardening rate or strain-ageing characteristics. It has no effect on the notch impact transition temperature of coarse grained Si-killed laboratory melted steel, in either the normalized or strain-aged condition, until the content reaches a value between 0·08 and 0·29%, when increasing arsenic promotes higher transition temperatures. The results reported by Houdremont suggested that arsenic raises the transition temperature of strain-aged fine-grained laboratory melted mild steel when the content reaches some value between 0·04 and 0·12%; this tends to confirm the work reported here but it should be noted that the transition temperatures are below 0°C.

### Comparison between the Literature Survey and Experimental Results

The survey suggested that the arsenic content of the plate must exceed 0·2% before any effect on weld-metal cracking can be observed.

The experimental work using E 7010 electrodes indicates that the arsenic content of the plate must exceed 0·10% in steel of the A.P.I. Grade *B* quality before it has any effect on hot cracking and must be very much greater (0·5%) to have any influence on weld-metal root cracking in highly restrained fillet joints.

In general, the conclusions reached from the experimental results on A.P.I. Grade *B* steel in respect of the effect of arsenic on weldability are similar to those deduced from the literature survey covering steels of higher sulphur and phosphorus.

In regard to the effect of arsenic on impact properties of this steel, caution must be exercised in applying the results obtained on laboratory melted heats to commercial casts of open-hearth quality mild steel, the former tending to show high transition temperatures compared with the latter.

Bearing this in mind, the lack of any effect of arsenic up to 0·27% on notch toughness, found by Kasatkin in respect of commercial rimming and killed steels, does not necessarily conflict with its effect on notch toughness of laboratory melted materials when present somewhere within the approximate range 0·10–0·27%, where an increase in the transition temperature was noted.

## SUMMARY AND CONCLUSIONS

The effect of arsenic on the weldability and notch toughness of mild steel to A.P.I. Grade *B* analysis has been studied by reference to published results on this grade of steel and on commercial rimming and killed steels and by experimental work on laboratory melted heats.

While some difference was noted in regard to the effect of arsenic on notch toughness as between laboratory and commercial steels, in general the experimental results do not conflict with published data.

It is concluded that arsenic must be present in the Grade *B* plate in excess of 0·10% to produce any effect on weld strength, ductility, freedom from cracking, or notch toughness.

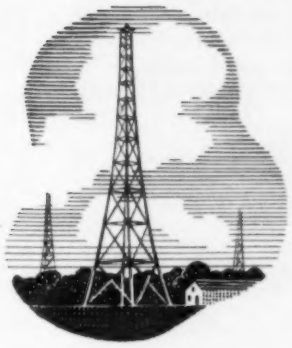
Furthermore, the same conclusions would be reached in respect of rimming or killed steels of higher sulphur and phosphorus contents than Grade *B* steel, provided that they are within the normal sulphur and phosphorus limits of 0·06% maximum.

It should be emphasized that to find any effects due to arsenic, it has been necessary to use much greater arsenic contents than would arise in normal steels; indeed the value of 0·10% arsenic, below which no effect is produced, is itself two or three times higher than the amount present in normal steels. Consequently there is no need to differentiate between steels of higher or lower arsenic content if this does not exceed 0·10%.

### REFERENCES

1. "Arsenic in steel." Bibliography No. 4, Iron and Steel Institute, 1937.
2. F. W. Harbord and W. A. Tucker: *J. Iron Steel Inst.*, 1888, vol. 32, No. 1, pp. 183–197.
3. J. E. Stead: *J. Iron Steel Inst.*, 1895, vol. 47, No. 1, pp. 77–140.
4. P. E. McKinney: *Chem. Met. Eng.*, 1920, vol. 23, p. 294.
5. A. E. Cameron and G. B. Waterhouse: *J. Iron Steel Inst.*, 1926, vol. 113, No. 1, pp. 355–374.
6. O. Bauer: *Mitt. deutsch. Mat.*, 1930, vol. 13, pp. 58–66.
7. J. Marchal: *Bull, Société d'Encouragement*, 1898, vol. 3, p. 1336.
8. P. Hahn: *Stahl u. Eisen*, 1925, vol. 45, pp. 7–9.
9. E. Houdremont, H. Bennek, H. Neumeister: *Archiv. Eisenhütt.*, 1938, vol. 12, pp. 91–101.
10. E. S. Kasatkin: *Stal*, 1956, vol. 16, No. 7, pp. 624–629.
11. D. Canonico and H. Schwartzbart: *Welding Eng.*, 1958, vol. 43, pp. 32–35.
12. T. Swinden and L. Reeve: *Trans. Inst. Welding*, 1938, vol. 1, pp. 7–24.
13. C. L. M. Cottrell: *Trans. Inst. Welding*, 1952, vol. 15, pp. 89r–92r.
14. P. T. Houldcroft: *Brit. Welding J.*, 1955, vol. 2, pp. 471–475.
15. E. C. Rollason and D. F. T. Roberts: *Brit. Welding J.*, 1954, vol. 1, pp. 441–447.

# NEWS
## *and Announcements*



*News of the Institute and Branches*
*B.W.R.A. · Other Societies · and Industry*

## INSTITUTE ACTIVITIES

### MEETINGS

**Conversazione: IIW work in hand**

On **4th February**, from 4.0 to 8.0 p.m., there will be a conversazione at the Institute, with a number of exhibits illustrating the technical work of the International Institute of Welding and the part which the United Kingdom Delegation is playing in it. Admission will be by invitation, and members who are interested and would like to have a ticket are invited to apply to the Secretary.

**Third Annual Lecture**

The Institute's Annual Lecture will be given by Mr. W. G. John, Deputy Director of Naval Construction, Admiralty, at the Institute on the evening of **Thursday, 3rd March.** The subject will be the influence of welding on naval architecture.

**Spring Meeting, Droitwich, May 1960**

The Spring Meeting of the Institute will be held at Droitwich from **9th to 11th May 1960,** and will be devoted to the novel welding processes and metal spraying.

**Tickets for Institute Meetings**

Some members have asked why tickets are occasionally required for admission to meetings of the Institute at 54 Princes Gate.

The Council wishes to make clear that the requirement is imposed upon the Institute among conditions attached to the use of the building. The safety requirements of the London County Council limit the number of persons who may be admitted to the Lecture Hall, and it is therefore necessary occasionally, when the limit might be exceeded, to issue tickets and restrict admission to those who have obtained them. When this is done, seats will be reserved for ticket holders until 10 minutes before the meeting is due to begin, and those who have not tickets will not be admitted to the Lecture Hall until 10 minutes before the start of the meeting, and then only to chairs still unoccupied. Whenever possible, arrangements will be made to relay lectures to the Library, where additional seats can be reserved when the Lecture Hall is full.

### NEWS OF MEMBERS

Mr. **T. McIver** (Member of Council) has just been appointed to the board of Swan Hunter and Wigham Richardson Limited.

**Obituary**

The Council regrets to record the deaths of:

Mr. **L. Van Ouwerkerk** who, although he only recently joined the Institute, was known to many members for the outstanding contributions which he and the Röntgen Technische Dienst N.V., of which he was Managing Director, made in the field of the non-destructive examination of welds. Until a few months ago, he had been for many years Vice-Chairman of Commission V—Testing, Measurement and Control of Welds—of the IIW, and was Chairman of its Radiography Sub-Commission. He also served as general *rapporteur* at the first World Congress of Non-Destructive Testing.

Mr. **F. Hadfield,** of the Manchester Branch, in November last (Associate-Member, 1936).

### CONTRIBUTORS TO THE JOURNAL

Dr. **G. R. Salter**, a Research Officer with the British Welding Research Association, graduated at Birmingham University with the degree of B.Sc. (Industrial Metallurgy) in 1955. He carried out research work into the absorption of gases by arc-melted metals

*G. R. Salter*

in the same department until 1958, when he was awarded the degree of Ph.D. He then continued this work as a University Research Fellow until September 1959, when he joined B.W.R.A.

### PUBLICATIONS

Reprints of the series of papers on "The Electric Arc in Welding" printed in this issue (pp. 71-128) and including the colour plate, are available from the Secretary of the Institute at 7*s* 6*d* a copy.

### SCHOOL OF WELDING TECHNOLOGY

The following courses have been arranged for February and March:

**Welding for Junior Management** (D.28)
**23rd–25th February**

This four-day course is designed to explain to those holding junior positions in management some of the factors affecting the proper application of welding.

**Inert-Gas Arc Welding** (D.11/1)
**7th–11th March**

The choice of process will be considered, and the welding techniques described and demonstrated. The application of the method to the welding of

light alloys and non-ferrous metals will be covered in detail.

**Welding Design and Construction in Corrosion- and Heat-Resisting Materials** (D.6/2)
**21st–25th March**

This repeats the previous course on the same subject but includes information on recent developments. The lectures cover the problems associated with the weldability of these materials, the choice of the most suitable welding process, and practical factors relating to the prevention of distortion and to jigging. The need for the correct approach to design for welding is emphasized in five of the 15 lectures.

**Institute's First Practical Training Course**

Between 4th and 15th January 1960, the first practical training course to be organized by the Institute was held at 54 Princes Gate. It was concerned with Ultrasonic Inspection and was a co-operative effort between the Institute and the three ultrasonic equipment manufacturers.

In the ultrasonic method of weld inspection, responsibility for the identification of internal defects lies with the operator of the equipment and the acceptance or rejection of a weld depends upon his interpretation of the trace on the cathode ray tube.

The operation of ultrasonic testing equipment demands more than manual dexterity, and before an operator is employed on anything but simple routine inspection he should have received a proper training in the fundamentals of ultrasonics and the principles and calibration of the equipment, and should be given a correct approach to the method of identifying weld defects. In response to many requests, the School of Welding Technology Committee decided that the Institute should provide training facilities for those who are to be entrusted with the use of ultrasonic equipment for weld examination.

The organization of the course was entrusted to a special panel, under the Chairmanship of Mr. B. R. Byrne, comprising J. W. Fox, A. C. Rankin, D. O. Sproule, T. J. H. Webborn, C. D. Wells, and P. Wiskin.

The course opened with a lecture on "*Basic Sound and Ultrasonic Wave Propagation*" by Mr. J. C. Cain, in the Lecture Theatre of the Science Museum. Then followed a lecture by Mr. D. O. Sproule on the "*Basic Principles of Ultrasonic Inspection*". He made use of simulation equipment which he had specially developed for the course. This equipment, which is shown in the accompanying illustration, is believed by many to be a big step forward in the training methods available. It simulates a piece of solid material by a volume of air in which are placed simulated defects of the form found in practice. The volume of air is scanned by a special ultrasonic wave generator and a receiver, and these are connected to the electronic part of the equipment, comprising a 9 in. oscilloscope display unit, pulse generator, and amplifier.

In ultrasonic inspection a knowledge of the form of the defects is of importance because it governs the nature of the reflected wave. The third lecture was therefore devoted to "*Characteristic Weld Defects*" and was given by Mr. T. J. H. Webborn. This was followed by a further lecture by Mr. Sproule in which the simulation equipment was used to indicate the characteristic reflections of defects found in welded joints.

The course then directed attention to the actual equipment used for inspection, and Mr. Rankin gave a lecture on the "*Principles of Ultrasonic Equipment*". This was followed by a practical period to enable students to become familiar with the equipment available in Britain for weld inspection. Mr. A. de Sterke then spoke about "*Initial Procedures for Fault Identification, Setting Up and Calibrating the Equipment*". Another practical period followed in which the students practised equipment calibration using a variety of reference blocks. Mr. de Sterke then gave two further lectures dealing with "*Procedure for Single Fault Identification*" and for "*Multiple Fault Identification*" respectively. There followed two further practical periods in which students attempted the identification of defects, firstly in sample welded joints containing one type of defect only and secondly in those containing more than one type.

For the practical periods the Institute has been extremely fortunate in obtaining a very large number of welded joints containing known faults. More than 120 sample plates were specially prepared for this course in plate thicknesses ranging from $\frac{3}{8}$ to 3 in. Most of the specimens were radiographed and the radiographs were available for inspection. This collection is probably the finest of its kind in the country and should prove of great value to the Institute in future courses on inspection and testing.

Mr. Webborn then gave a lecture on the "*Identification of Faults in Pipe and Tube Joints*" and this was followed by a practical period in which sample welded pipe joints containing known faults were examined.

The instructional part of the course closed with a lecture by Mr. J. W. Fox on the "*Identification of Faults in Other Types of Welded Joints*" and with a practical period on this subject. The last day of the course was devoted to an assessment period, during which the students were invited to attempt the identification of defects in three weld samples. The results of their attempts were discussed with them.

The Institute gratefully records its thanks to the following three British suppliers of ultrasonic testing equipment

*Mr. D. O. Sproule demonstrating simulation equipment*

*Students working during a practical session*

for their generous help in providing equipment and specialists for the practical periods:

Kelvin and Hughes (Industrial) Limited;
Solus-Schall Limited;
Ultrasonoscope Co. (London) Limited.

The Institute is also extremely grateful to the following companies who have co-operated in the preparation of the samples and radiographs used in the practical periods of the course:

W. S. Atkins & Partners (samples)
B.I.X. Ltd. (radiography)
British Aluminium Co. Ltd. (aluminium samples and radiography)
Central Electricity Generating Board (samples)
Displays (display equipment)
Esab Ltd. (samples)
Firth-Vickers Stainless Steels Ltd. (stainless steel)
G. A. Harvey & Co. (London) Ltd. (samples and radiography)
Inspection Services Ltd. (radiography)
International Combustion Ltd. (samples and radiography)
Robert Jenkins & Co. Ltd. (welding of stainless steel samples)
Murex Welding Processes Ltd. (samples and radiography)
Quasi-Arc Ltd. (samples and radiography)
Pantak Ltd. (radiography)
Rockweld Ltd. (samples and radiography)
The Unit Superheater & Pipe Co. Ltd. (samples and radiography)
George Wimpey & Co. Ltd. (samples)

## BRANCH NEWS

### East Midlands

**Welding thick material**

A meeting of the Branch was held at the College of Art, Derby, on Monday, 16th November, 1959, when a paper on "*Developments in Heavy Gauge Resistance Welding*" was given by Mr. A. G. Gallé.

Mr. Gallé said that when resistance welding heavy gauges, it is generally necessary to take the machine to the job, which demands a portable head, longer arms on the machine, and consequently high current losses. It is therefore necessary to employ a higher kVA.

Even after cleaning heavier gauge plates, there are minute high spots which are blown off if welding is carried out in the normal way. To assist in overcoming this, welding pressures at the tips of up to 50,000 lb/sq.in. are required. Pre-heating also helps to overcome this trouble, and this is achieved by applying a low current, slowly rising, to burn off oxides, applying a high pressure, then a normal welding pressure, and then returning to a high pressure.

A large number of slides were shown, and these included:

1. A portable resistance welding machine slung on a travelling gantry
2. The welding of car wheel hubs onto the rims, employing eight welds, each about the size of a penny, and stated to show a large saving compared with riveting.
3. A fixed speed rotating table for spot welding small components, with automatic ejection of the welded components.
4. The welding of brackets to a metal car dashboard which has a PVC skin covering. Current cannot be passed through the PVC, and is fed in on a return pad, along the metal to the welding tip, avoiding heat transfer to the PVC.

K.H.E.

### Leeds

**Good welding design**

At the opening technical meeting of the Branch on the 7th October, a lecture was given by one of the Branch members, Mr. M. Birkhead. He described in great detail all the factors necessary for the manufacture of welded fabrications of good quality.

He made the point that although not all vessels are Class I, they all should be first class, and the necessity for good design, careful preparation of the individual items, correct welding technique, including the method of welding, followed by careful inspection should result in work done being of good quality.

Mr. Birkhead gave examples of some of the faults that can arise and he stressed the need for some knowledge of metallurgy, particularly when dealing with alloy steels and non-ferrous metals.

A very real discussion followed the lecture and many expressed their pleasure that a lecture had been given by a member of the Branch.

**Modern shipbuilding techniques**

Shipbuilding in England has always been subject to the cold blast of severe competition, very often subsidized competition, and yet has always been in the forefront of the industry.

A paper prepared by Mr. W. R. Mellanby, M.I.N.A., M.I.W., which was repeated at the Leeds Branch on the 27th October, describes how one shipbuilder is leading the industry in modern technique and a courageous departure from traditional methods.

These new methods require no alteration in design or drawing. The change starts in the moulding loft where men already employed were trained in the new procedure. Templates drawn to one-tenth scale are photographed and the resultant negative is either fed into the automatic flame cutting machine or projected from the optical marker. The first vessel made by this method was launched in 1958 and Mr. Mellanby paid tribute to the way the workmen adapted their traditional skills to this complete change.

The main reasons for this new method were, economy, both of the use of labour and space, and the fact that production engineering methods could be more readily used.

The accuracy of the method gave some concern and tests over a period of eight weeks were made to check this factor, but once the principle was established the method proved to be extremely good and resulted in better workmanship and less adjustment of erected units on the ship.

As was to be expected, there was a long discussion following the lecture, and Mr. Rhodes, who gave the paper in the absence of Mr. Mellanby, was warmly thanked by Mr. Cochrane for the very satisfactory replies he made to the many questions.

**Brains Trust a must**

On 17th November, the Branch meeting took the form of a Brains Trust and the panel was chosen to cover Drawing Office and Design, Metallurgy, Workshop Practice, and Equipment and Supplies. Several questions ranging from electrode holders to stress corrosion in the shell of a crude coal gas condenser were dealt with.

The discussion was very vigorous and the Chairman, Mr. Gardener, had to call a halt to the proceedings only because of the shortage of time. Everyone present thought that the meeting was very worth while, and it was decided to make it an annual event.

C.B.

### Wolverhampton

**Strain measurement**

On Friday, 27th November, at the Old Wulfrunian's Club, Mr. E. Procter (John Thompson Ltd.) lectured to an audience of 27 members and 3 visitors on "*Industrial Application of Strain Gauges*".

Mr. Procter gave a convicing demonstration of the principles of the electric resistance strain gauge in its simplest form, and went on to discuss the different types of gauge used in practice and the methods of manufacture, giving indications of the wide field of work in which they can be employed to the benefit of engineers.

The basic fundamentals of measurement were also explained with the aid of special equipment, and Mr. Procter

mentioned straightforward standard measuring equipment which was now available and could be adapted to suit different types of work. Some of the methods used for switching for multi-point work and their advantages and disadvantages were mentioned.

Methods of compensation for temperature changes were discussed, and Mr. Procter stressed the importance of sound methods and techniques in the choice of gauge surface preparation, application, cementing, and protecting of gauges to ensure accurate results.

Some of the charts and diagrams used to simplify the task of obtaining the correct recording of results from a large number of gauges, were shown.

Mr. Procter concluded a particularly interesting and well presented paper by stating that the electric resistance strain gauge was becoming an invaluable tool for engineers.

During the subsequent discussion, a variety of questions were asked, and the meeting concluded with a vote of thanks proposed by Mr. Shields and seconded by Mr. Dipper. B.K.B.

## BRITISH WELDING RESEARCH ASSOCIATION

### London Office

The address of the London Office of the Association is now 19 Fitzroy Square, London W.1 (Tel. Euston 9595/6).

### Symposium on Fatigue of Welded Structures

The British Welding Research Association and the Engineering Department of Cambridge University are jointly organizing a symposium under this title. This is to be held in the Engineering Department, Cambridge University, from Tuesday, **29th March** to Friday, **1st April, 1960.**

A full discussion on the subject of fatigue of welded structures is thought to be of considerable importance at the present time. A good deal of research has now been done, but the expansion of welding fabrication in many areas where fatigue strength is a criterion is revealing new aspects of the problem. Present knowledge might therefore be usefully consolidated and new aspects considered by those people who are directly concerned with and interested in the investigation of the fatigue of welded structures.

Several papers will be presented by experts, and will include contributions from the United States of America and from East Germany. These will deal primarily with structures fabricated by fusion welding processes.

The fee for membership of the symposium is 15 guineas. Further particulars may be obtained from the British Welding Research Association, Abington Hall, Abington, Cambs.

## DIARY

**2nd Feb.—East Midlands**—"*Welding and the draughtsman*" by H. B. Merriman (Victoria Station Hotel, Nottingham, 7.15 p.m.)
**Eastern Counties**—"*Welding in the Structural Industry*" by F. Brooksbank (City College and Art School, Norwich)

**3rd Feb.—Manchester**—"*Welding in the modernization of the railways*" by P. S. A. Berridge and G. D. S. Alley (College of Technology, 7.15 p.m.)

**4th Feb.**—Conversazione, "*IIW work in hand*" (54 Princes Gate, 4.0 to 8.0 p.m.)
**North Eastern (Tyneside)**—"*Welding and ship salvage*" by E. P. Wilson (Mining Institute, Neville Hall, Newcastle, 7.0 p.m.)

**8th–12th Feb.—School of Welding Technology**—Course D.22 "Welding of Atomic Energy Plant"

**8th Feb.—West Wales**—"*Modernization of British Railways* (*Western Region*)" by M. G. R. Smith and R. A. Smeddle (Swansea Technical College, 7.0 p.m.)
**Sheffield**—"*A practical approach to the problem of distortion*" by J. S. Waring (Grand Hotel, 7.15 p.m.)

**9th Feb.—East Wales**—"*Argonarc welding of corrosion and heat-resisting steels*" by J. A. McWilliam (Park Hotel, Cardiff, 7.0 p.m.)
**Liverpool**—"*The Runcorn/Widnes bridge project*" by J. K. Anderson (College of Technology, 7.30 p.m.)
**North London (Slough Section)**—"*Design for welding*" by F. Brooksbank (Community Centre, 7.30 p.m.)
**South Western**—"*The foundation of stress relieving*" by Dr. R. Weck (Radiant House, Bristol, 7.15 p.m.)

**10th Feb.—South London**—"*Construction of liquid methane cold storage plant*" by D. Slater and H. F. Goodman (Joint meeting with **North London** Branch) (54 Princes Gate, 7.30 p.m.)
**Preston**—"*Plastics materials in engineering*" by A. Clarke (Joint meeting with Institution of Production Engineers) (Harris Technical College, Barrow-in-Furness, 7.15 p.m.)

**12th Feb.—Leeds**—Dinner Dance (Mansion Hotel)

**16th Feb.—Leeds**—Lecture by A. A. Smith of B.W.R.A. (Great Northern Hotel, 7.30 p.m.)

**17th Feb.—North Eastern (Tees-side)**—"*Manufacture and distribution of industrial gases*" by R. A. Exton (Cleveland Scientific and Technical Institution, Corporation Road, Middlesborough, 7.30 p.m.)
**West of Scotland**—"*Shipyard reorganization for welded contruction*" by R. Straton (Institute of Engineers and Shipbuilders, Glasgow, C.2, 7.0 p.m.)
**South London**—Joint meeting with the **North London** Branch. "*High pressure pipelines in the gas industry*" by F. W. Bell (54 Princes Gate, 7.30 p.m.)

**18th Feb.—Southern Counties**—"*Welding in atomic energy research*" (tentative) (Technical College, St. Mary's, Southampton)

**19th Feb.—Birmingham**—"*Resistance welding research*" by E. J. French (Grand Hotel, 7.30 p.m.)

**22nd–25th Feb.—School of Welding Technology**—Course D.28 "Welding for junior management"

**23rd Feb.—Eastern Counties**—To be arranged (Norwich)

**25th Feb.—Eastern Counties**—"*General safety precautions in relation to compressed gas cylinders*" by T. Reeks (North East Essex Technical College and School of Art, Colchester)

**26th Feb.—Preston**—"*The inquisitive giant*" (Jodrell Bank radio telescope) by C. N. Kington (Technical College, Barrow-in-Furness, 7.15 p.m.)
**Wolverhampton**—Paper on metallization (Wulfrunians' Club, 7.30 p.m.)

**1st Mar.—Eastern Counties**—"*Welding of pressure vessels and nuclear power plant*" by B. K. Barber (Eastern Electricity Board, Ipswich)
**South Western**—"*Welding and the draughtsman*" by H. B. Merriman (Bristol Aircraft Co. Ltd., Filton, 7.15 p.m.)

**2nd Mar.—Manchester**—"*Welding in the structural industry*" by A. V. Hooker (College of Technology, 7.15 p.m.)

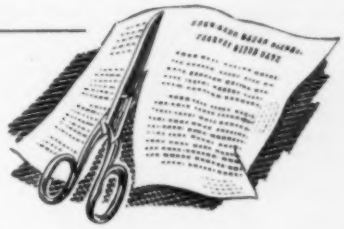
**3rd Mar.**—Third Annual Lecture by W. G. John (54 Princes Gate, 5.30 p.m.)
**North Eastern (Tyneside)**—"*Welding from the standpoint of the rules of the American Bureau of Shipping*" by R. T. Young (Mining Institute, Neville Hall, Newcastle, 7.0 p.m.)

**7th–11th Mar.—School of Welding Technology**—Course D.11/1 "Inert-gas arc welding"

**7th Mar.—West Wales**—"*Inert-gas metal-arc welding of aluminium*" by A. R. Woodward and E. M. Wilson (Swansea Technical College, 7.0 p.m.)

**8th Mar.—East Wales**—"*Inert-gas metal-arc welding of aluminium*" by A. R. Woodward and E. M. Wilson (Llandaff Technical College, Cardiff, 7.0 p.m.)
**Liverpool**—"*Uses and welding of Hastelloy*" by R. Owen (College of Technology, 7.30 p.m.)
**East of Scotland**—"*Preheating and stress relieving power sources*" by R. McGlashan (Lyceum Gallery, Atholl Crescent, Edinburgh, 7.30 p.m.) (Joint with Edinburgh Electrical Society)

# *Current* WELDING LITERATURE



*Book Reviews*

*Additions to the Institute Library*

*Trade Publications*

## CONTENTS OF PERIODICALS RECIEVED

*This section is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the* Bibliographical Bulletin of Welding and Allied Processes, *published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.*

### Welding Journals

*Australian Welding Journal*, 1959, vol. 2, July

**Welding as applied to steel castings,** F. Cleggett (7–9)

**Welded cantilever trusses form basic framework of elevated school building,** Omer Blodgett (18–19)

**Welding speeds production of steel ducting** (21)

**Reclamation of hammer-mill hammers by welding** (24–25)

**Photography in the welding industry,** R. D. Boyle (27–28)

*Australian Welding Journal*, 1959, vol. 2, August

**Welding applications in modern power stations** W. Gibb and N. A. Falconer (7–11)

**The welding of cast iron,** K. L. Hoath (17–21)

**California's all-welded viaduct points the way to improved design** (23–25)

*Australian Welding Journal*, 1959, vol. 3, September

**The selection of steels for welded structures,** H. Muir and J. S. Hoggart (12–25)

**King Street Bridge project design of superstructure and welded high tensile steel girders,** R. T. A. Hardcastle (26–32)

**A review of the principles, processes used and recent advances in the fusion welding of aluminium,** W. A. Gardner (41–47)

**Some practical aspects of the fusion welding of aluminium,** G. S. Swinbourne (55–61)

*Journal of the Japan Welding Society*, 1959, vol. 28, No. 8

**Construction of light-alloy torpedo-boats,** J. Iwai (4–10)

**Welding in the chemistry in Japan,** T. Naka and others (11–18)

**Some notes on the effect of aluminium content upon underbead weld crack sensitivity of Mn–Si high tensile steel,** S. Hasebe (19–24)

**Continuous cooling transformation diagrams of various steels submitted to welding,** H. Sekiguchi and M. Inagaki (Report 3, 25–32; Report 4, 33–38)

**The shapes and compositions of non-metallic inclusions in mild steel weld metals, Report 1,** K. Kato and K. Nakai (39–44)

**On the max. arc length in metal arc welding,** F. Oshiba and K. Shimizu (45–49)

**Study on an automatic electric arc welding, Report 2,** F. Oshiba and K. Shimizu (50–54)

*Przeglad Spawalnictwa* (Poland), 1959, vol. 11, October–November

**Problems of brittle fracture in welded steel structures,** A. A. Wells

**Welded structures evaluation,** W. Soete

**Influence of welded stresses in brittle fracture initiation in welded structures,** A. Fabiszewski

**For the proper evaluation of welding work quality in shipbuilding,** M. Mysliwiec

**Electrodes in shipbuilding,** F. Richter

**Choice of economic method of weldment inspection in shipbuilding,** M. Jakubiec

**Economy in steel St 52 application in welded structures,** A. Neumann

**Results of tests on flame-cutting improvement and on gas economy,** W. Schierhorn

**Technology of welding on slipway timber cargo ship B514–5900 TDW,** Z. Unterschutz

*Revue de la Soudure Lastijdschrift* (Belgium), 1959, vol. 15, No. 3

**Repair by welding of a welded structure with rigid joints by the Institute of Civil Engineering at the University of Liège,** H. Louis (119–129)

**Reloading with the help of base alloys of borides of chromium in the sugar industry,** E. Sellier (130–135)

**The use of welding and allied techniques in maintenance works and the repair of railway rolling stock,** J. Daivier (136–146)

**Brittle resistance of cracked plates,** W. Soete (147–152)

**Measurement of flexibility of welded cables** (153–155)

**Results of studies undertaken by the International Institute of Welding Commission V on the use of gauging blocks for the purpose of control in ultrasonic testing apparatus** (156–166)

*Schweissen und Schneiden* (Germany), 1959, vol. 11, October

**The influence of welding on the application of plastic materials,** O. Dammer (385–388)

**Surface protection by sintering and flame spraying with plastic powders,** E. Gemmer (389–393)

**Determination of the damage done by excess oxygen during gas welding,** H. Fiehn (393–396)

**Model experiments with machine tool elements,** J. Bielefeld (396–401)

*Schweisstechnik* (Germany), 1959, vol. 9, October

**The prospects of welding development in the USSR,** G. A. Nikolajew (358–362)

**Welding collaboration,** C. Miklosi (363–364)

**Welding development planned up to 1965 and welding equipment and filler metal requirements,** W. Anders (365–367)

**Overburden conveyer bridges of welded construction in the German Democratic Republic,** R. Hagemann (367–371)

**A technical and economic comparison of arc welding transformers, rectifiers and generators,** H. Krusche (372–376)

**X-ray quality butt-joint assemblies, Part I,** K. G. Reinhardt and W. Knauer (378–385)

**Submerged arc hard-facing of high-duty conveyor chain links in lignite mining,** O. Tanzer (386–390)

**Does welding of grey cast iron require a surplus of acetylene?** H. Jahre (390–394)

*Welding Design and Fabrication* (U.S.A.), 1959, vol. 32, October

**The strength of arc welded joints, Part 2** (29–31)

**Engineers have more flexibility when designing welded bridges** (32–33, 72, 74)

**Stainless combined with A-7 steel solves 8 ft. valve design problem** (34–35, 74)

**$CO_2$ welding set-up makes two joints in one automatic cycle,** (36 and 74)

**Heat treating low-alloy high tensile steel weldments** (44–45)

**Heavy plate fabrications used in 60,000-pound steel lift truck** (46–47)

**A single code for all welding?** Howard Cary (50, 52)

*Welding Engineer* (U.S.A.), 1959, vol. 44, October

**Welding the reactive metals,** L. M. Gourd and F. W. Copleston (43–44)

**Eliminating contamination is a prime consideration when welding titanium,** T. M. Laurenson (46–49)

**How to weld zirconium and its alloys,** L. E. Stark (50–51)

**Resistance spot welding of tantalum studied at Battelle,** J. J. Vagi and R. L. Koppenhofer (52–53)

**Tig process produces strong, ductive welds on tantalum,** A. F. Busto (54–56)

**Glycerine—an important factor in the welding industry,** C. F. Brown (73–75)

**Are you using the right size ignitron?** J. S. Kirk and D. O. Purvear (78–79)

*Welding Journal* (U.S.A.), 1959, vol. 38, October

**The principles of the modern arc torch,** R. M. Gage (959–962)

**With proper equipment, tooling and procedures, thin-gauge large assemblies can be fabricated by fusion welding precipitation-hardening steels,** R. Meredith (963–968)

**Ultrasonic welding of aluminium,** F. R. Collins and others (969–975)

**Dip-transfer carbon-dioxide welding,** R. W. Tuthill (976–981)

**One of the principle applications of extrusions in tank fabrication,** M. J. Cohen (982–986)

**A new system for automatic feedback control of resistance spot welding,** G. R. Archer (987–993)

**Gas-shielded metal-arc welding used in fabricating intricate processing controls,** G. Hartwick and G. Warren (994–997)

**Spray hard surfacing increases service life of fans 20 times,** J. E. Looney and S. L. Newcom (998)

**Welding of Nickel-Molybdenum alloys,** G. M. Slaughter and others (393s–400s)

**Electron beam welding,** G. Burton and W. L. Frankhouser (401s–409s)

**Welding of beryllium,** E. L. Brundige and others (410s–413s)

**Prestrain, size and residual stresses in static brittle-fracture initiation,** C. Mylonas, (414s–424s)

*Zeitschrift fur Schweisstechnik* (Switzerland), 1959, vol. 49, October

**Ultrasonic examination of welded joints, Part I,** R. Hornung (284–289)

**New welded constructions in light metal hydro-electric machinery,** M. H. Walser (290–295)

**The first course in Switzerland for gas shielded arc welding,** C. G. Keel and H. P. Siegenthaler (296–299)

*Zvaranie* (Czechoslovakia), 1959, vol. 8, October

**Rust resistance test of fluxes,** E. Stalmasek (290–299)

**Weldability of 17% chrome steel with titanium addition,** M. Vyklicky (299–301)

**Magnetic properties of electro-slag welded joints,** M. Mosny (301–304)

**Thermal treatment of electro-slag welds,** J. Vrtel (304–309)

**Repair of a 200 t shear,** R. Rohan and J. Kristek (309–311)

**Contribution to the safety in gas welding and oxygen cutting,** M. Kopriva (311–313)

**Improvement of cooling water supply in argon welding sets,** J. Vodera (314)

## Other Journals

**Shielded-arc welding with argon and tungsten electrode** (*Brown Boveri Review*, 1959, vol. 46, March, pp. 210–220)

**Resistance welding electrodes** (*Copper*, 1959, No. 7, Winter, pp. 18–21)

**Resistance welding in relation to design,** E. J. French (*Engineering Materials and Design*, 1959, vol. 2, November, pp. 549–553)

**Aluminium brazing paste saves $175,000 at Martin,** D. Wernz and M. Schwartz (*Steel*, 1959, vol. 145, October 12, pp. 112–114)

**Applications and problems of metal spraying—a review of the process in the Union of South Africa,** J. F. Attwell (*Electroplating and Metal Finishing*, 1959, vol. 12, April, pp. 138–140)

**Hard facing reduces maintenance costs,** N. D. Berrick (*Engineering*, 1959, vol. 188, October 30, pp. 426–427)

**A new method of positioning honeycomb panels and assemblies during fluoroscopic and radiographic examination,** H. E. Harris and J. C. Schneeman (*J. Soc. for Nondestructive Testing* (U.S.A.), 1959, vol. 17, May–June, pp. 152–155)

**Early detection of fatigue in metal alloys by ultrasonics** K. Sittel (*J. Soc. for Nondestructive Testing* (U.S.A.), 1959, vol. 17, May–June, pp. 165–171)

**Radiography with a large cobalt 60 source,** V. G. Behal (*J. Soc. for Nondestructive Testing* (U'S.A), 1959, vol. 17, May–June pp. 172–176)

**On the radiographic merits of the 1000 PKV resonant transformer and the Van De Graaff X-ray generators,** D. E. Alliott and C. M. Knowles (*J. Soc. for Non-destructive Testing* (U.S.A.), 1959, vol. 17, July–Aug., pp. 205–209)

**Progress in technology and equipment for eddy current inspection,** H. L. Garbarino and H. N. Newrin (*J. Soc. for Non-destructive Testing* (U.S.A.), 1959, vol. 17, July–Aug., pp. 229–234)

**Magnetic and penetrant methods of non-destructive testing,** H. J. Bezer (*The Inspection Engineer*, 1959, vol. 23, September–October, pp. 97–102)

**An introduction to ultrasonic testing, Part 4,** W. E. Schall (*The Inspection Engineer*, 1959, vol. 23, September–October, pp. 103–106, 102)

**Summary of the SNT symposium on stainless steel brazed honeycomb structures,** R. C. McMaster (*J. Soc. for Non-destructive Testing* (U.S.A.), 1959, vol. 17, September–October, pp. 263–269)

**The immersed ultrasonic inspection of metal plate,** R. W. McClung (*J. Soc. for Non-destructive Testing* (U.S.A.), 1959, vol. 17, September–October, pp. 270–275)

**The development of ultrasonic methods for material testing in Poland,** L. Filipczynski and I. Malecki (*J. Soc. for Non-destructive Testing* (U.S.A.), 1959, vol. 17, September–October, pp. 276–280)

# LOOK–there's the fault!

**Once again MAPEL pinpoints the hidden fault—in what appeared to be a faultless weld.**

The MAPEL Welding Inspection Service can save you thousands of pounds, providing skilled advice on the best techniques, procedure and practice . . . training welders to high standards . . . testing welds speedily by visual, radiographic and the latest ultrasonic methods.

**Call in MAPEL for Welding Inspection; also for Cathodic Protection and Leak Detection.**

**Get the facts from**

**METAL & PIPELINE ENDURANCE LTD.,**
30, London Road, Woolmer Green, Knebworth, Herts
Tel: Knebworth 3083 (8 lines). Cables: Metaldure, Knebworth.

**MAPEL**

*Other offices at London, Newcastle-upon-Tyne and Glasgow*

**WORLD-WIDE SERVICE**

# When the 'right time' is essential

in process cycles

or welding current duration

## depend on AEI electronic timers

GENERAL PURPOSE AND PROCESS WORK—TYPE FU 21

- Available from stock in timing ranges covering 0·5 to 180 seconds
- No moving parts in timing circuit
- Easily arranged to operate in individual control schemes
- High repetitive accuracy
- Suitable for 40/60 cycle a.c. supplies of 110, 200/250, or 400/440 volts

WELDING—TYPE FW 19

- For control of resistance welding machines
- Timing range 0·1 to 10 seconds
- No moving parts
- Supplied with separate rheostat for remote setting
- Available from stock for immediate delivery

*Please write for further technical details and a copy of our brochure 'Electronics in Industry'. Our engineers will be pleased to help you with your automatic timing problems.*

AEI

**Associated Electrical Industries Limited**

**Electronic Apparatus Division**

NEW PARKS, LEICESTER, ENGLAND

A5385

# "TAKE MY TIP— USE SIFBRONZE EQUIPMENT!"

*says Will the Welder*

**"DEMON" BLOWPIPES:—**
General Duty and Cutting Models.

**SIF-COLIBRI CUTTING MACHINE**
The clockwork machine which turns a hand cutter into a precision machine cutter. Ideal for flame cutting on site.

**SIF-COMBI PROFILE CUTTING MACHINE**
An automatic dual-purpose machine for all kinds of cutting work.

**SIFBRONZE REGULATORS**
Modern precision instruments giving constant pressure and volume.

**SIFBRONZE CATSEYE GOGGLES**
The most advanced type on the market.

*If you want to know how Sifbronze equipment can help you, fill in the coupon right away.*

SUFFOLK IRON FOUNDRY [1920] Ltd., Stowmarket, Suffolk.

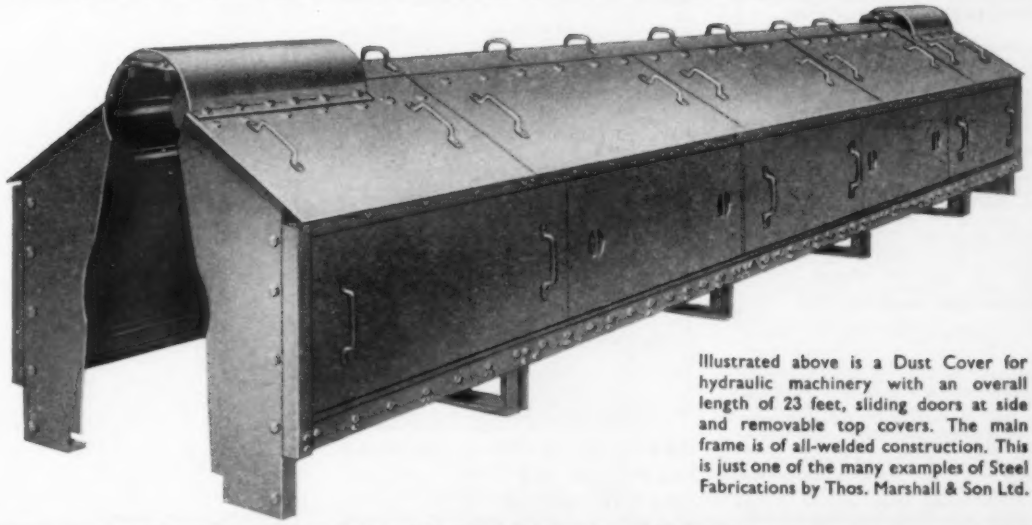
*Please send me leaflets detailing Sifbronze equipment.*

NAME .....

ADDRESS .....

.....

BWJ/C/1



Illustrated above is a Dust Cover for hydraulic machinery with an overall length of 23 feet, sliding doors at side and removable top covers. The main frame is of all-welded construction. This is just one of the many examples of Steel Fabrications by Thos. Marshall & Son Ltd.

# STEEL FABRICATIONS BY THOS. MARSHALL & SON LTD.

WELLINGTON BRIDGE, LEEDS, 12 · 'GRAMS: 'CISTERNS' LEEDS, 12 · TEL. 32186 (5 lines)

## RESISTANCE WELDING CURRENT METER

**Designed to measure short pulses of heavy current**

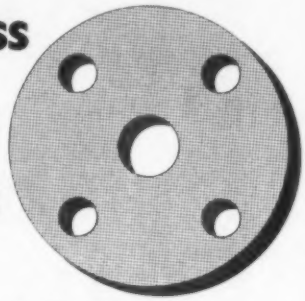
The standard instrument has 6 ranges covering readings of 100 to 100,000 amps. The readings are obtained by the use of toroids which can be split and placed around the heavy current conductor. Indication is stored enabling readings to be taken minutes after the weld is made.
Can be used with welders employing synchronous and non-synchronous and energy storage controls.

HED

*Illustrated leaflet sent on request*

**HIRST ELECTRONIC LTD.**
GATWICK ROAD, CRAWLEY, SUSSEX

## STAINLESS TUBES & FLANGES



We offer in approved grades of Stainless Steel

- **FLANGES MACHINED TO B.S. TABLES OR TO SPECIAL SIZES**
- **SOLID DRAWN TUBES—FABRICATED PIPES**
- **ROUND and HEXAGON BAR**
- **PROFILES CUT TO ANY THICKNESS OR SIZE**
- **CASTINGS TO CUSTOMERS' SPECIFICATION**

*Keen Prices—Prompt Delivery*

Send enquiries to Dept. B.W.J.

**STAINLESS STEEL PROFILE CUTTERS LTD.**
Farfac Works, Kings Grove, MAIDENHEAD
*Telephone:* 1522/23


# CLASSIFIED ADVERTISEMENTS

## APPOINTMENTS VACANT

Applications are invited for the appointment of a

**WELDING ENGINEER**

A degree in engineering or metallurgy, or equivalent qualifications, is necessary, together with a sound knowledge of modern welding technology covering all classes and types of welding encountered in the structural engineering industry. Overall supervision of labour and negotiations with Trade Unions at shop floor level will be involved. Starting salary will be in accordance with the applicant's age and experience. Applications, giving full details of experience, which will be treated in strict confidence, should be addressed to: The Works Manager, THE UNITED STEEL STRUCTURAL CO. LTD., Frodingham Works, Scunthorpe, Lincs.

**Welding Engineer Supervisor** required, age 30–40, with up-to-date practical experience in submerged-arc and other systems of welding and of weld testing techniques. The appointment offers excellent prospects of advancement. Candidates must possess organizing ability, initiative, drive and accept responsibility for control of small number of personnel engaged on a new expanding development. Contribution pension scheme and good canteen facilities. Apply, stating salary required, to the Personnel Officer, The British Steel Piling Co. Ltd., Claydon, Suffolk.

---

"B.O.C." SIZE 55 TYPE H UNIVERSAL CUTTING MACHINE for sale. Suitable for oxy-acetylene, oxy-propane or oxy-coalgas with suitable nozzles. Largest cut 9 ft 3 in. Largest circle 4 ft 7 in. diameter. Largest rectangular surface area 16 sq.ft. Motor drive suitable for 230 volts d.c. Automatic circle cutting gear with graduated radius bar for cutting without templates. Cuts from ¼ in. to 24 in. thick. Magnetic tracer roller, template support and nozzle. F. J. Edwards Limited, 359 Euston Road, London, N.W.1, or 41 Water Street, Birmingham 3.

NEW ½ in. GUILLOTINE for sale. EX STOCK. Motorized overcrank type. Cutting width 8 ft 4½ in. Auto hold-down and all necessary gauges. Depth of gap in open ends 9½ in. Weight 17½ tons. Photo etc. from F. J. Edwards Limited, 359 Euston Road, London, N.W.1, or 41 Water Street, Birmingham 3.


FIFTEEN YEARS' SERVICE

has proved RENTWELD dependability.
This is why more and more HIRERS are becoming PURCHASERS of RENTWELD arc welding transformers.

TODAY this value is unsurpassed and is available to you.
For details phone GUL. 6006/7/8

**RENTWELD LTD., 94 Camden Road, London N.W.1**

**BRAND NEW OIL-IMMERSED OXFORD ARC WELDING TRANSFORMERS WILL GIVE YOU A LIFETIME OF SERVICE.**

Fully guaranteed sets—110 amp **£25**, 180 amp **£45**, 250 amp **£71**, 300 amp **£85**, 350 amp **£99 10s.**, 450 amp **£135**, etc. Also Two-operator 180, 250 and 300-amp Models, ex stock.

Send for leaflets and booklet from Britain's largest electric welding plant stockists.

**C. G. & W. YOUNG**
**15A COLNE ROAD, TWICKENHAM. POP. 5168**


One "Holmes" 400/3/50, 48 h.p., five operator, 150 amp. Welding Generating Set; one "Eisler" 75 kVA. Spot & Butt Welder; eight "Metro Vick" 22·5 kVA. Atomic Hydrogen Welders; one heavy duty "Birtly" 400/3/50, Welding Manipulator with 52 in. square plate; also large stocks of Stainless Steel Welding Electrodes in 6, 8, 10, 12, 14's gauge by Murex, Rockweld, and Quasi-Arc; all new in maker's original packing. Lists available. Low prices.
WOODFIELD & TURNER LTD.
CANNON STREET, BURNLEY. Tel.: 78134

## ADVERTISERS' INDEX


| | |
|---|---|
| Associated Electrical Industries | |
| Electronic Apparatus Division | 26 |
| Instrumentation Division | 18 |
| Transformer Division | 12 |
| British Industrial Gases Ltd. | *Inside Front Cover* |
| British Oxygen Gases Ltd. | *Outside Back Cover* 11 |
| Crompton Parkinson Ltd | 16 |
| Distillers Co. Ltd., The | 6 |
| Firth Vickers Stainless Steels Ltd. | 10 |
| General Electric Co. Ltd., The | 2 |
| Hancock & Co. (Engineers) Ltd. | 3 |
| Harvey, G. A. & Co. (London) Ltd. | 7 |
| Hirst Electronic Ltd. | 28 |
| Ilford Ltd. | 13 |
| Imperial Chemical Industries Ltd. | 17 |
| Jenkins, Robert | 5 |
| Johnson Matthey & Co. Ltd. | 14 |
| 12th Liege International Fair | 15 |
| Lincoln Electric Co. Ltd. | 22 |
| Marshall, Thomas & Son Ltd. | 27 |
| Meritus (Barnet) Ltd. | 15 |
| Metal & Pipeline Endurance Ltd. | 25 |
| Milne, C. S. & Co. Ltd. | 4 |
| Norton Grinding Wheel Co. Ltd. | 24 |
| Nu-Swift Ltd. | 1 |
| Quasi-Arc Ltd. | 8, 9 |
| Research & Control Instruments Ltd. | *Inside Back Cover* |
| Saturn Industrial Gases Ltd. | 19 |
| Stainless Steel Profile Cutters Ltd. | 28 |
| Suffolk Iron Foundry Ltd. | 27 |
| Yates Plant Ltd. | 20 |
| Classified Advertisements | 28 |




Published by THE INSTITUTE OF WELDING, 54 Princes Gate, London, S.W.7
Made and Printed by Percy Lund, Humphries & Co. Ltd., London and Bradford

# *Solve your production problems with*

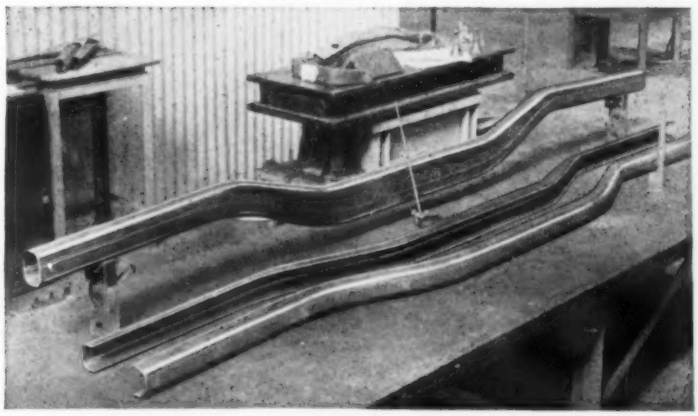
# PHILIPS

## *bare wire*

## *$CO_2$ welding machine*

Philips AUTOMATIC $CO_2$ *bare wire* welding process is now available for immediate delivery in Britain. With this machine you can speed up mass production of welded parts, for example main chassis members, bottled gas cylinders, car wheels. And you can get welds protected from nitrogen and hydrogen by an atmosphere of $CO_2$ — which costs only a fraction of the price of argon. The absence of coating reduces the absorption of hydrogen, too.

- Welds very wide range of steel grades.
- Needs no stocks of expensive powders.
- Cuts labour costs by welding faster, requiring little attention in repeat operations.
- Welds are homogeneous with deep and even penetration.
- Arc is self-regulating . . .
- Nitrogen and hydrogen content low — no nitrogen porosity.



Component parts and finished vehicle chassis side member welded by Philips $CO_2$ process. *(Photo by courtesy of John Thompson Motor Pressings Ltd.)*

**Philips Automatic $CO_2$ welding machine**

provides automatic wire and $CO_2$ feeds Travelling carriage moves along rails at speed set by operator. Water-cooled nozzle independent of main water supplies. Single control lever engages wire feed, switches on carriage motor and arc.

*For further information about Philips $CO_2$ welding, and about Philips Automatic welding machine (a product of N.V. Philips, Eindhoven) write to:*

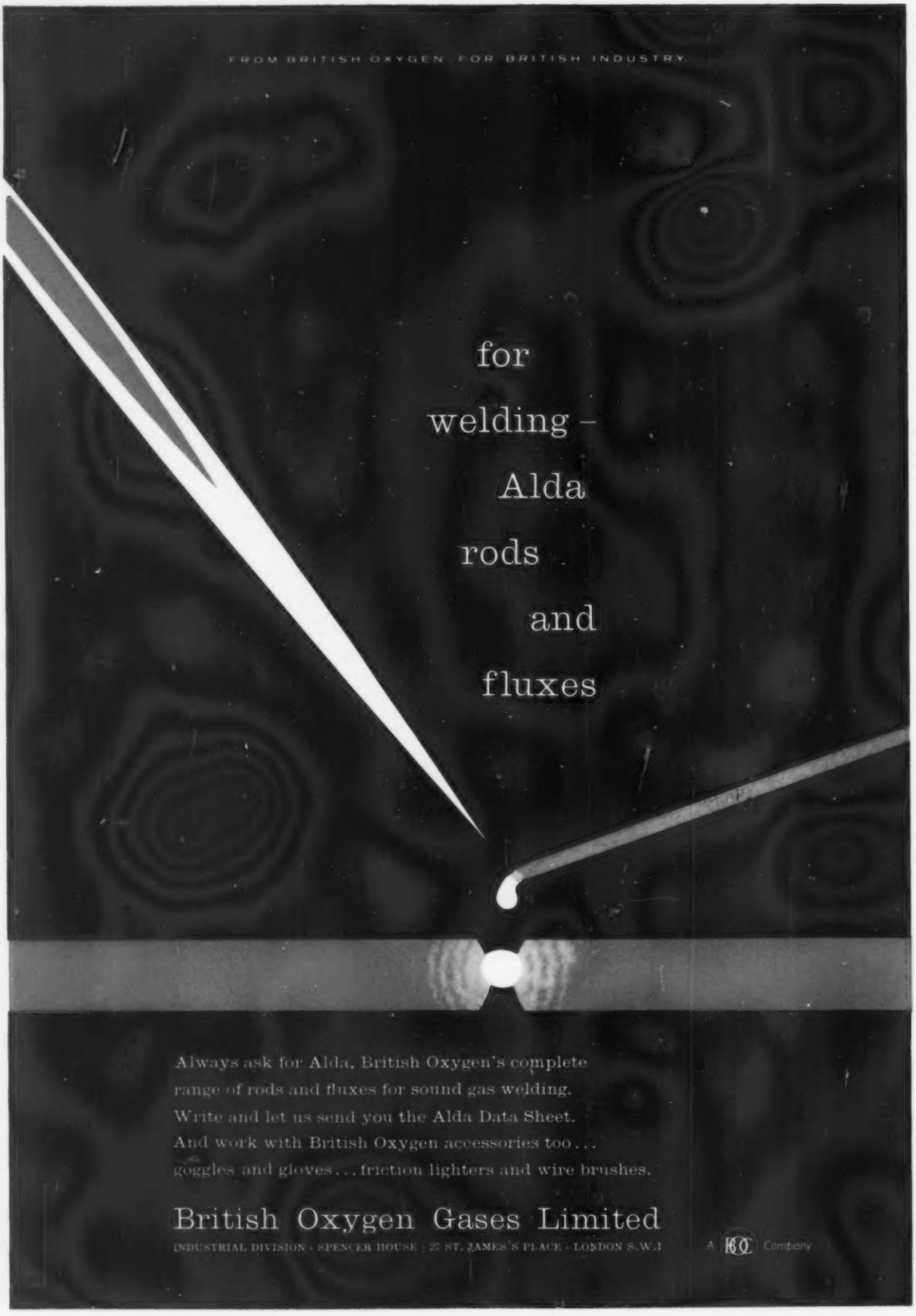
*Sole Distributors in the U.K.:*

## RESEARCH & CONTROL INSTRUMENTS LTD.

207 King's Cross Road, London, W.C.1. *Telephone : TERminus 2877.*

(P10311)

*Inside back cover*


FROM BRITISH OXYGEN · FOR BRITISH INDUSTRY
for
welding –
Alda
rods
and
fluxes
Always ask for Alda, British Oxygen's complete
range of rods and fluxes for sound gas welding.
Write and let us send you the Alda Data Sheet.
And work with British Oxygen accessories too...
goggles and gloves... friction lighters and wire brushes.
British Oxygen Gases Limited
INDUSTRIAL DIVISION · SPENCER HOUSE · 27 ST. JAMES'S PLACE · LONDON S.W.1
A BOC Company

*Outside back cover*